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***Abstract* -** The lack of proficient real-time traffic monitoring systems is one of the major bottlenecks of Advanced Traveller Information Systems (ATIS) and Advanced Traffic Management Systems (ATMS). In this report we describe a method of collecting real-time traffic data from probe vehicles automatically sending traffic reports to one or more base stations, connected to a traffic center by a wired communications network. Analyzing and computing road traffic and message traffic flows in the San Francisco Bay Area, we study several multi-disciplinary aspects of this data collection technique, such as the relation between vehicle traffic and message traffic, the influence of road traffic congestion on communication performance, the reliability of road traffic estimates on radio network throughput and the location of base stations. The results presented in this report reveal that random access (ALOHA) transmission of traffic messages is a (spectrum) efficient, inexpensive and flexible method for collecting road traffic data and that this approach can provide reliable traffic monitoring. Not only highly accurate real time link travel times can be estimated, but also Automatic Incident Detection (AID) can performed.

Keywords: Advanced Driver Information Systems, Advanced Traveler Information Systems, Advanced Traffic Management Systems, Mobile Communication systems, Telecommunication, Traffic Surveillance

Note: With this report, a floppy disk is available containing a simulation/animation and a numerical analysis of the performance of an ALOHA' radio network for collecting road traffic data from probe vehicles in the San Francisco Bay Area.

Executive Summary

This report addresses a techniques to gather real-time travel times from vehicles functioning as moving traffic 'probes'. Each probe vehicle keeps track of its own geographic position using, for instance, dead-reckoning or GPS satellite positioning. At random time intervals, each probe vehicle transmits its average or instantaneous speed and its travel time, over a radio link such that it may be received by a nearby base station. A wired communication network connects all base stations in a specific area to a Traffic Management Center (TMC), where the received data is processed.

The radio link forms a major bottleneck of any wireless data collection technique. Several communication protocols and transmission media can be used for data transfer from the roving probe vehicles to a receiver installed in each listening base station. In this report, we analyze the probe vehicle concept, focusing on communication aspects. We address a random access radio architecture that is simple, inexpensive and spectrum-efficient for the probe vehicle transmissions. We have developed the computer tool PROMOT (PRObe vehicle concept for Monitoring road Traffic) to evaluate this concept in a realistic metropolitan traffic situation.

The most significant communication parameters effecting the proficiency of the probe vehicle concept for collecting real-time road traffic data appear to be the propagation distance of the traffic messages transmitted by probe vehicles and the probe vehicle penetration rate. In particular, the effects of these parameters are studied in this report. Conform the characteristics of random access ALOHA, the results of the computer tool show that beyond a certain distance, the number of traffic messages received in the base stations from a road link substantially decreases as the distance between the base station and the road link increases.

At low probe vehicle penetration rates (up to circa 1 %), the maximum distance from where transmitted messages are still received is approximately 25 kilometers. Path loss and noise are the main mechanisms of packet loss and the radio channel design is amply sufficient to accommodate the message traffic flow.

At moderate vehicle penetration rates (circa 1 to 5 %), the number of attempted messages increases, which initially increases the number of successfully received messages. At the same time, channel capacity limits the message throughput and increases the probability of a harmful collision with other messages. As a result, the cell size of the base stations is limited to a radius of about 14 kilometers. From the links within this cell, a large number of messages are received successfully. The smaller cells necessitate more base stations, but the combination of more probe vehicles and more base stations is notably beneficial for the throughput per road link.

At high probe vehicle penetration rates (more than circa 5 %) the traffic message throughput diminishes, even from the road links nearby the base station. In this case the transmission interval T has to be adjusted to assure adequate traffic monitoring. In this way, a solid traffic monitoring system can be constructed with a high quality performance under all circumstances (low, moderate and high probe vehicle penetration rates) that is suitable for all aspired applications (Automatic Incident Detection and (Advanced) Traffic Management / Traveler Information Systems).

Table of Contents

<u>Appendices</u>

List of Figures

1 Introduction

For Advanced Traffic Management Systems (ATMS) and Advanced Traveler Information Systems (ATIS), accurate and reliable information is needed to observe and to control the traffic flow. In particular information about real-time travel times, speeds, real-time origins and destinations and disturbances of the traffic flows are of great importance (Westerman, 1994B). Elementary traffic data can be collected by a data collection system along the road infrastructure. Such systems mostly use inductive loop detectors. These fixed detectors typically provide instantaneous speeds and occupancy at the location of the detector. The desired traffic information subsequently has to be deduced from these data. Estimation of the real-time travel times and real-time origins and destinations requires complex and time demanding analyses (Westerman, 1994A), while disturbances in the traffic flows due to incidents can only be detected when they have propagated to the location of a fixed detector. Although these methods may be suitable for several mid term, long term and semi-dynamic traffic management decisions, the complexity, the analysis-time and the propagation delay are prohibitive for more advanced traffic control measures, such as ATMS and ATIS (Westerman and Hamerslag, 1993; OECD, 1992). This is especially the case for a statewide or nationwide traffic monitoring network, with large distances between the locations of the fixed detectors. Advanced traffic control systems need more reliable, more accurate and more detailed real-time traffic data, both on network level as well as on specific traffic bottlenecks.

To meet the input data requirements of ATM/IS, new techniques have to be developed for data collection and processing. In this report, we study a data collection technique where the source of real-time traffic data are the vehicles themselves, functioning as moving traffic ‘probes’ (Ran, 1993). By means of onboard electronics, each probe vehicle keeps track of its own geographic position using dead-reckoning based on wheel sensors, a compass and a digitized road map, (differential) GPS satellite positioning or hybrid positioning schemes. Each probe vehicle transmits its travel experiences, i.e. its average or instantaneous speed, and travel time, on a radio channel such that it may be received by a nearby base station. These transmissions occur at random, but nonetheless more or less regular time intervals. In the European SOCRATES program their messages are called ‘floating car data’. All base stations in a specific area are connected to a Traffic Management Center (TMC) by a wired communication network. At the TMC, the received probe vehicle data is processed into road traffic information and travel advisories.

One of the major bottlenecks of such a system is the volume of messages and the capacity of the wireless communication link between probe vehicles and the base station. Several communication protocols and transmission media can be used for data transfer from the roving probe vehicles to the receivers in the listening base station, each having its own advantages and disadvantages. In this report, we will analyze the probe vehicle concept, focusing on communication limitations. We address a radio communications concept that is simple, inexpensive and spectrum-efficient for the probe vehicle transmissions. We developed a computer tool called PROMOT (PRObe vehicle concept for MOnitoring road Traffic) to evaluate this concept in a realistic traffic situation.

The organization of the report is as follows. In chapter 2, the probe vehicle system concept is described. Chapter 3 describes the structure of the PROMOT computer tool. Each sub-model of this tool and its results are discussed in a separate paragraph. The tool starts with a road-traffic flow calculation for the freeway network of the San Francisco Bay Area. Subsequently, the throughput of the proposed radio network is analyzed. This specifies the relation between the spatial distribution of the messages transmitted by the probe vehicles and the throughput of successfully received in the base stations. In chapter 4 the case study of road traffic and message traffic in the San Francisco Bay Area is presented. This chapter is descriptive and relatively self contained. The figures in this chapter are mostly screen prints from PROMOT. Chapter 5 presents the results of the case study. The effects of several communication parameters on the system performance are analyzed. Particular attention is paid to the effect of probe vehicle penetration rate. This results in a specification of the requirements for monitoring the complete freeway network in the San Francisco Bay Area, using floating car data. In chapter 6 general and specific properties of the probe vehicle system using random access radio channel are discussed. Chapter 7 concludes this report.

2 Probe Vehicle System Concept

The application of telematics in traffic and transport has already resulted in the deployment of a number of (Advanced) Traveler Information and Traffic Management Systems (ATIS / ATMS). Examples are the U.S. Transport Advisory Radio (HAR and AHAR) and systems where subcarrier voice or data messages are added to the audio and video signals on FM and TV transmitters. The European Radio Data System/Traffic Message Channel (RDS/TMC) system, the German Autofahrer Rundfunk Information (ARI) and the British CARFAX all use FM subcarrier transmission for disseminating data to travellers. ATIS services like in-vehicle electronic mapping, real-time travel information and dynamic route guidance are under development (Walker, 1990). ATIS may help motorists in finding optimal routes to their destinations, so they lead to individual user optima. By means of several ATMS applications such as ramp coordinated metering, variable message signing and automatic incident detection it tries to reach an optimal overall *system* performance (system optimum). It has been observed in the past that the user optimum may differ from the system optimum.

The real-time traffic data required to generate ATIS service messages and deploy ATMS applications can be gathered from police and local authorities, sensors (Levy, 1992), weather stations and air surveillance. Few systems are yet operational that gather real-time road traffic data automatically. As travel times between two points are more reliable than measurements of the speed of vehicles at one particular point along the road, (probe) vehicles participating in the road traffic and automatically reporting the (link) time needed for travelling between two intersections are a useful source of road traffic data.

Figure 1 depicts a generic lay-out of a system in which traffic data is collected by probe vehicles and several other monitoring sources (road sensors, police, authorities, air surveillance, etc.) and gathered at a Traffic Management Center (TMC) (Westerman, Linnartz and Hamerslag, 1994). The TMC processes this data and takes corrective actions (e.g. ramp metering), supplies information (e.g. variable message signing) or disseminates information directly to the car drivers (e.g. travel advisories, traffic information and dynamic route guidance). Here we focus on the communication link between probe vehicles and the TMC. We do not consider strategies for processing probe data (centralized, decentralized, user optimum, system optimum, etc.).

Future IVHS may offer a wider variety of applications and services. It is desirable to use common communication facilities for multiple services. A description of a possible solution for an ‘integrated IVHS services’ network using a single (30 kHz radio) channel has been documented in a PATH working paper (Linnartz, 1994). This design distinguishes *downlink* messages from the TMC to vehicles and *uplink* messages from vehicles. Downlink transmissions has been subdivided into datacasting from the TMC to all vehicles or groups of vehicles and messages from the TMC to one or more specific (probe) vehicles. Uplink messages from vehicles via base stations to the TMC and can be subdivided into emergency messages from a probe vehicle in danger, random-access messages (e.g. information queries, Automatic Vehicle Location/Identification), and probe data (unprocessed road traffic data). Each of the distinguished subclasses has its distinct traffic requirements. Spectrum efficiency can be optimized if communication solutions are tailored to each traffic category. This report is limited to uplink probe transmissions.

We would like to emphasize that for the application considered here, there is no need for full-duplex communication. Acknowledgements of received messages are not needed. Uplink data gathering from probes and downlink datacasting may be implemented without interaction of the message traffic streams. The single-channel communication solution (Linnartz, 1994) separates uplink (probe) transmissions and downlink dissemination of traffic information into different logical communication channels. At the physical level, the separation is done in the time domain, but the medium-access and network (routing) protocols also differ per traffic category. Despite the fact that only a fraction of all available time slots is available from probes, the analysis of the system is similar to the situation where one channel is used exclusively for probes.

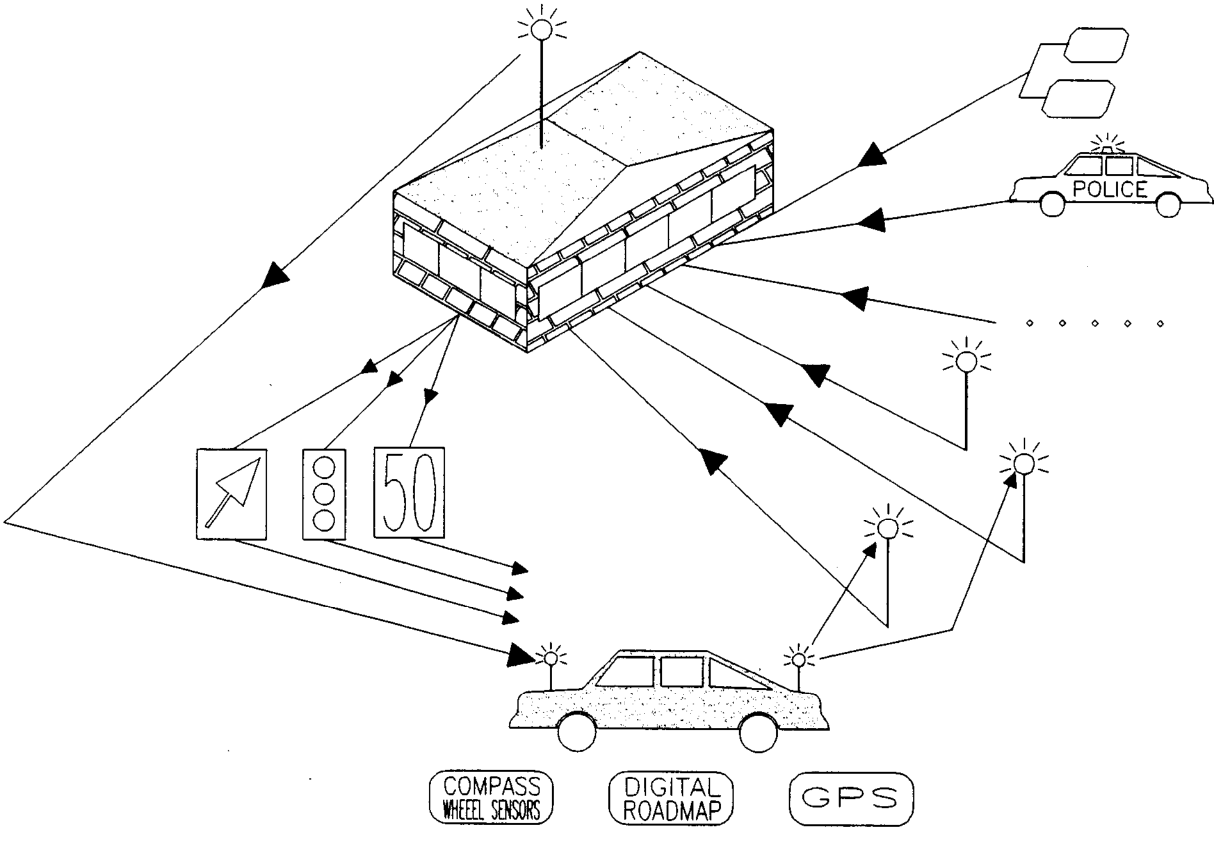


Figure 1 Lay-out of genetic probe vehicle system concept

2.1 Related Research Activities

Prototypes of systems using intelligent vehicles and hybrid communication media to collect road traffic data have already been developed (OECD, 1992).

The EURO-SCOUT system (EURO-SCOUT, 1991), for instance, uses infrared spectrum for line-of-sight communication between vehicles and roadside beacons. These beacons are connected to a TMC by a wired infrastructure. Several pilot projects (LISB, 1991; OECD, 1992) showed promising results. However, a major disadvantage of this system concept is the large number of beacons needed for a sufficiently dense coverage of an urban area. Another disadvantage is that disturbances in the traffic flow can only be detected when vehicles have propagated to the vicinity of a beacon. For Automatic Incident Detection this may take too long.

Another probe vehicle system concept under development is SOCRATES (Catling and Op de Beek, 199 1). This telematic system is designed to operate independently of particular choice of the radio communication link. It is being designed to allow the use a modified version of the pan-European digital cellular mobile network GSM, allowing packet communication. An advantage of this approach is that little extra dedicated communication infrastructure is needed. Circuit-switched telephone networks are fundamentally inefficient for short data messages, as for instance generated by probes. In order to provide more suitable features and a more efficient data transmission capability, a short message service and other data services are being developed and standardized. This extension is called the General Packet Radio Service (GPRS) (Cattling , 1994).

2.2 Radio Access

Radio appears an appropriate medium for wireless probe communication. One solution could be to assign dedicated radio channels for collecting road traffic data from probe vehicles. With multiple base stations in a regular cellular frequency reuse pattern, nationwide or statewide coverage can be achieved. Radio access can be granted through a ‘polling’ scheme, in which vehicles are interrogated about their location and travel experiences. Polling schemes require substantial management efforts (transmission of synchronization signals, handovers to other base stations, updating the transmission sequence of vehicles leaving a cell, etc.) which may significantly reduce the efficiency. Moreover, issues with respect to privacy are very arduous with polling schemes.

Another possibility, which we address here, is not to coordinate vehicle transmissions at all. All vehicles in a cell transmit on the same common radio channel, in any available time slot, regardless of the possibility of transmission of travel data by other probe vehicles. This scheme is called the ALOHA access protocol (Abramson, 1977). It operates as follows: probes transmit traffic messages at random instants of time, accepting the risk of mutual interference between messages. If multiple messages interfere with each other, because of radio-wave propagation effects, the signals are likely to be received with substantially different power. In such case, the strongest signal is likely to capture the receiver, while the weaker messages are lost (e.g. Abramson, 1977; Linnartz, 1993). Signals from remote probes may capture other base station receivers at different locations. In standard ALOHA systems, the base station broadcasts a acknowledgement for all successfully received messages. Unsuccessful messages are retransmitted after a random waiting time.

Our application significantly differs from the usual ALOHA schemes where any lost message is retransmitted automatically. In our application, we omit acknowledgements. The loss of one particular travel report does not result in a retransmission: we would rather see a more recent report from another vehicle in a next time slot. This also implies that there is no need for acknowledging successfully received messages, as in conventional ALOHA radio networks. Unlike the conventional ALOHA system, where excessive retransmissions may cause system instability, our proposed system is not subject to such problem. The network performance parameter most relevant to our application is the successful throughput per road segment per time (or per minute).

Mobile ALOHA radio networks with a single base station have been researched extensively in the last years. The main conclusions can be summarized by

- The maximum throughput can significantly exceed l/e (36.8 %) because of receiver capture
- The mobile ALOHA channel is significantly more stable than the wired (LAN) ALOHA network
- Control of the number of admitted users (and their total average traffic load) in the system can be effective to ensure stability. This is in sharp contrast to dynamic control of the retransmission back-off time, as required in wired ALOHA networks.
- Throughput does not decrease rapidly to zero for large traffic loads
- The point of operation does not have to be at relatively low traffic loads
- Remote terminals have a lower probability of successfully transmitting their messages than nearby terminals. Remote terminals nonetheless benefit from capture as it diminishes the traffic intensity of strong interfering packets.
- Error correction redundancy does not increase throughput significantly if the channel is ‘slow fading’, i.e. if received powers are fairly constant during the packet duration
- Error detection schemes should be more effective than for wired communications over Additive White Gaussian Noise (AWGN) channels
- The throughput for spatially uniform offered message traffic is independent of packet traffic load.
- Adaptive antennas and signal processing are very effective to enhance the throughput
- Packet transmissions are preferably much shorter that the coherence time of the channel fading

In earlier evaluations (Linnartz, 1993), we addressed network with multiple base stations and frequency reuse in packet-switched networks. The throughput appeared to be optimum if one assigns the same time slots on the same frequency simultaneously in all cells. In such case, a probe does not have to know in which cell it is located and transmissions occur regardless of a frequency reuse pattern. A base station can accept any received probe report, regardless of whether it is transmitted within or outside its particular cell. This offers ‘site diversity’ reception from probe vehicle messages as one traffic message may be received by multiple base stations (Linnartz, 1992). This scheme allows us to use the same radio channel in a large area contiguously, without using different frequencies in adjacent areas, as is common practice in cellular telephone nets. Listening base stations, connected to a fixed backbone network, can be located throughout the system operational area. A network planning tool for the fixed backbone between base stations is being developed within the PATH program by Prof. Walrand at U.C. Berkeley.

2.3 Receiving Base Station

A base station considered in the single-channel network design (Linnartz, 1994) contains transmit and receive facilities, a (PC-style or dedicated) computer system, a GPS receiver for synchronization and connection to a high speed digital backbone. A base station receives messages from probe vehicles during a certain percentage of time and it supports other IVHS services during the rest of the time. It is however possible to add additional, inexpensive base stations to achieve a higher throughput of probe vehicle messages at a particular location. This requires no further system modifications. Such an auxiliary base station does not need transmit and synchronization facilities. As illustrated in figure 2, it simply consists of an antenna, a digital receiver, a message buffer, a simple processing unit and a telephone modem.

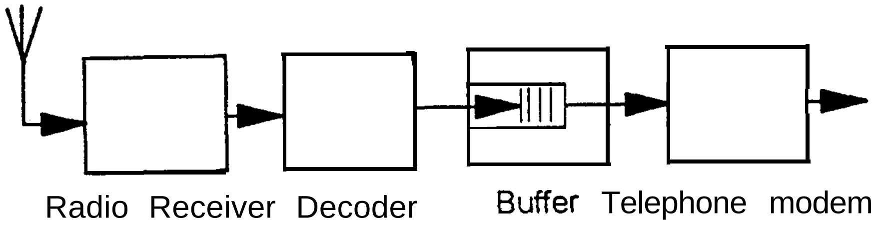


Figure 2 Receiving Base Station for collecting probe vehicle data

In the network under study, all base stations listen to the common ALOHA channel and transfer any successfully received probe message to the TMC. In our single-channel design, we offer about f_s = 18 time slots per second for probe vehicles

As we will compute later, the successful throughput per base station per second is on the order of S_0 (typically $S_0 \approx 0.32$) times f_s. Each probe message contains at most $\boldsymbol{L} = 260$ bits. The throughput is thus $\boldsymbol{L} S_0 f_s \approx 1.5$ kbit/s per base station. As some communication capacity may also be needed for remote control and telemetry of the base station, a 2400 baud telephone link may introduce some queuing delay of probe messages when they are transferred to the TMC. A telephone link with a 14.400 or 9600 baud modem should be amply sufficient to transfer data from the base station to TMC at negligible queuing delay.

2.4 Probe Vehicle Terminal

Figure 3 shows that for intelligent vehicles already equipped with a navigation system, the additional equipment needed for the proposed radio system is limited to a radio modem and some data processing in the in-vehicle controller.

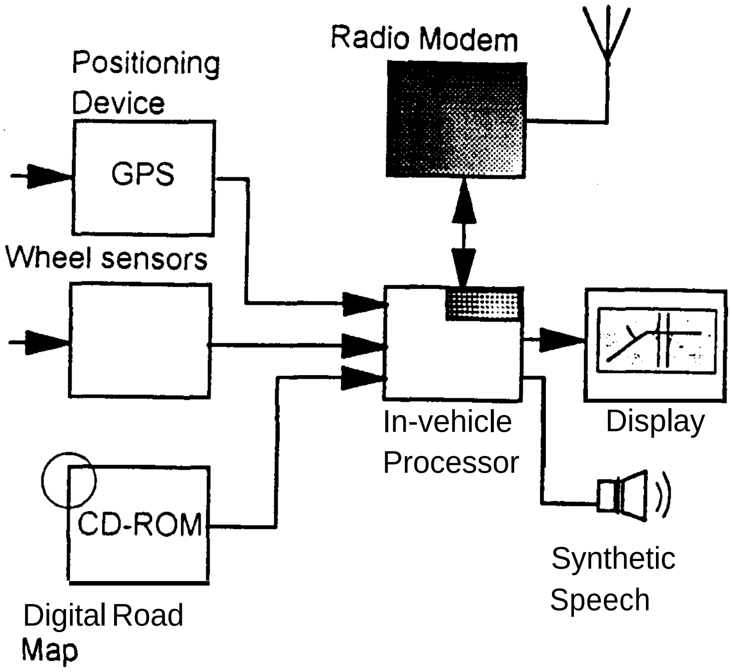


Figure 3 Block diagram of typical
in-vehicle navigation system and radio modem

The radio modem contains a receiver, for receiving traffic advisories from the TMC as they are datacast to all vehicles, or receiving data messages for interactive ATMIS services. These downlink signals offer slot synchronization that allows the vehicle terminal to find the appropriate slots for transmitting probe date. Also, we will show later that for optimum performance the TMC needs to specify the average inter-transmission time of the probes. This requires an occasional (downlink) datacast message to all probes.

3 Integral Model for Road and Radio Network Analysis

In order to evaluate the probe vehicle concept in a realistic traffic situation, we have estimated road traffic flows on the freeways in the San Francisco Bay Area. From these road traffic flows, message traffic flows transmitted by the probe vehicles can be estimated. These message traffic flows have been used for a performance analysis of the ALOHA transmission protocol. This chapter suformulates the model for the road and radio network flows.

3.1 Introduction

An integral model, covering road traffic aspects as well as data communication aspects, has been developed. This model has been called PROMOT (PRObe vehicle concept for MOnitoring road Traffic) and consists of several sub-models. The composition of PROMOT is sketched in figure 4. The Transportation model (sub-models 3 through 7) computes origins and destinations of road traffic in the San Francisco Bay Area. These results are indispensable for estimating road traffic flows and travel times, but the underlying theoretical principles are not relevant for this study. For this reason this model will mainly be captured through references.

The next paragraphs outline the scope and purpose of each PROMOT sub-model and present their results. We also indicate how we transfer parameters that are computed and defined in one sub-model into other sub-models.

Road and Public Transport Network Specification (sub-models 1 and 2)
The starting point is a network sub-model of the transportation infrastructure, including private as well as public transport. This represents the existing road and public transport network in the San Francisco Bay Area. Nodes (concentrations of population and employment) and connecting links (roads and rail with specific capacities) are used. Section 3.2 describes the abstracted networks for our study.

Transportation Model (sub-models 3 through 7)
The Origin-Destination (O-D) Matrix is an essential component for computing road traffic flows. It specifies the number of vehicles coming from and heading to the different network nodes. A measured OD-matrix for peak hour traffic was not available for this study, so we estimated one. To this end, we modified an existing model of combined multi-modal static interaction and we applied elastic land-use constraints (Hamerslag, 1994). This model calculates the number of departures and arrivals (trip ends) of each specified zone. It assumes accessibility to be the main factor influencing land-use. The model is an extension of the traditional four-stage transportation model which is a step-wise approach to production/attraction, distribution, mode choice, and assignment (see for instance: Manheim, 1979). In our case however, the distribution and mode choice are calculated simultaneously. Therefore, it uses elastic, rather than fixed constraints. In this way, the land-use data (employment and working population) that are traditionally exogenous in a fixed constrained interaction model, are computed endogenously.

Sub-model 3 computes the number of trip ends in each zone from the employment and working population using several trip purposes. The ‘generalized time’ is calculated for trips between origin-destination pairs, both for the road travel (sub-model 4) and for the public transportation (sub-model 5). Here ‘generalized time’ expresses an average of different sacrifices needed for traveling, such as travel time and costs, expressed in units of time. Based on these generalized times, sub-model 7 distributes the trip ends over the network along the shortest routes between every zone. Traffic measurements have been used for verification of the resulting O-D matrixes. Section 3.3 covers the transportation model.

Traffic Assignment (sub-models 8 - 10)
The former computations result in an origin/destination (OD)-matrix for car trips and one for public transport trips. In sub-model 8, the road OD-matrix is assigned to the road network. This results in traffic flows on each road link. Sub-model 9 does the same for public transport. The transportation model thus provides the traffic flow and mean travel time for each road link (sub-model 10). Section 3.4 discusses the assignment and its results.

Generation of Traffic Messages (sub-models 11 and 12)
A certain percentage of the vehicles serves as probes that transmit traffic messages. Sub-model 11 determines the number of probe vehicles on a road link directly from the computed traffic densities on each road link. Alternatively, in sub-model 12, we simulate each probe vehicle traveling from its origin to its destination. In both cases, we assume that a probe vehicle transmits its location and its travel time over the last (fraction of a) road link. The optimum content and data format of the traffic messages is still a subject for investigation. We assume that vehicles perfectly know their location, for instance through a hybrid GPS and deadreckoning positioning technique. The generation of traffic messages is discussed in section 3.5.

Calculation of Spatial Throughput (sub-models 13 and 14)
The traffic messages can be received by base stations located in the area under study. In the ALOHA radio network, harmful interference between messages transmitted in the same time slot (collisions) may occur. In our investigations, message collisions are taken into account using models for receiver capture and mobile radio-wave propagation (sub-model 13 for the analysis and sub-model 14 for the simulation). The calculation of spatial throughput is discussed in section 3.6.

Performance of IVHS Services (sub-model 15)
The final result of the integral model is an overview of the number of received traffic messages and their locations for each base station. The analysis further estimates the number of messages that are received at multiple base stations simultaneously. It relates this number to the number of messages needed to perform several IVHS services (sub-model 15).

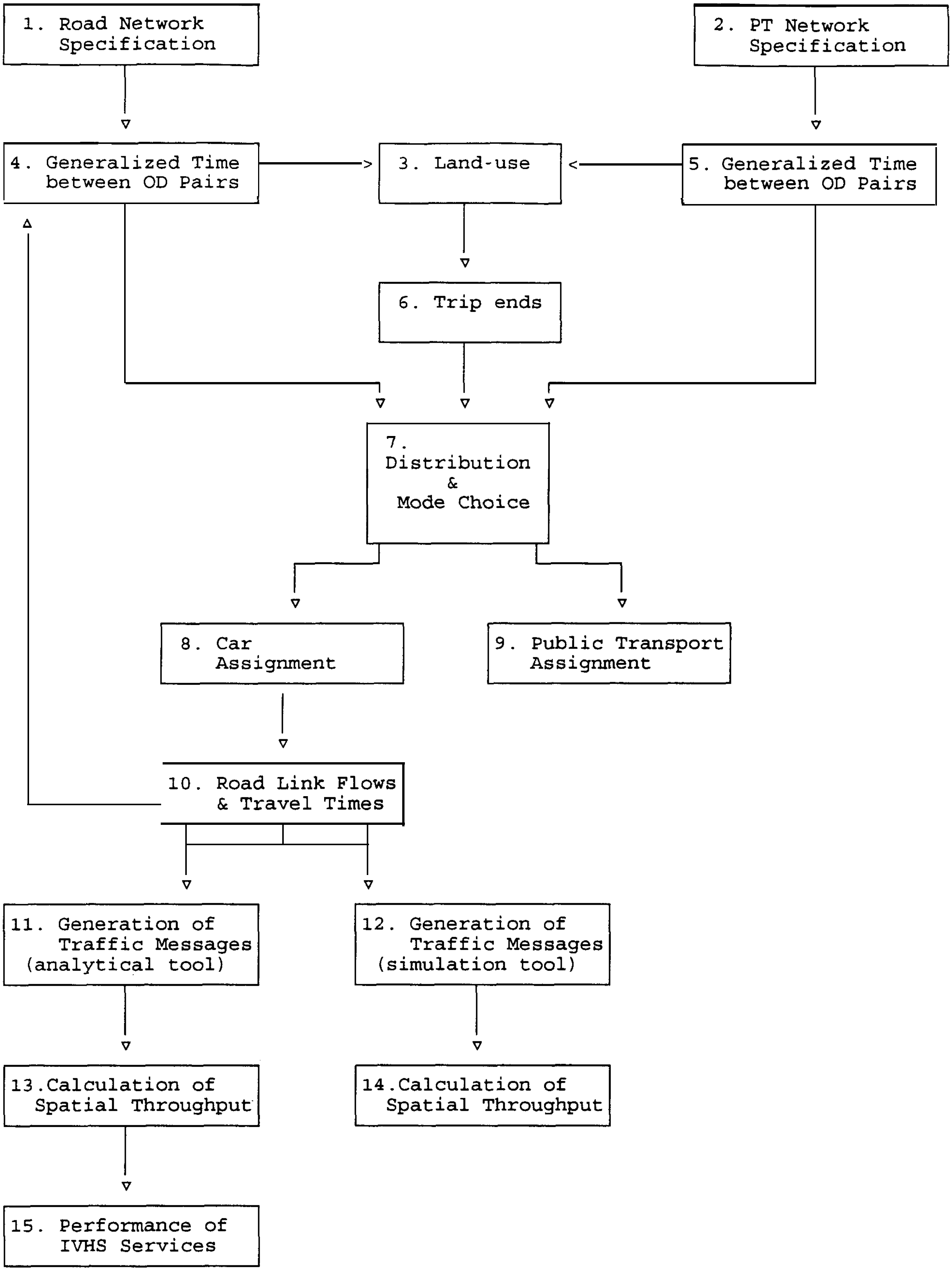


Figure 4 Composition of the integral model for road traffic and data communication PROMOT (PRObe vehicle concept for MOnitoring road Traffic)

3.2 Road and public transport network specification

For the network specification (sub-models 1 and 2), we took the San Francisco Bay Area (San Francisco - Oakland - San Jose). This area was divided into zones. Zones are network nodes with most important attributes ‘dwelling’ and ‘employment’. These nodes are connected by links, representing the road infrastructure. Each trip starts and ends in a certain zone.

Figure 5 shows the abstracted road network of the San Francisco Bay Area. This abstracted network has been limited to the major roads (mostly highways) and comprises 40 zones. For the traffic flow calculation, a number of public transport lines has been added (see figure 6). In appendices B and E, the attributes of the abstracted road and public transport network respectively, such as capacities and free flow speeds are given.

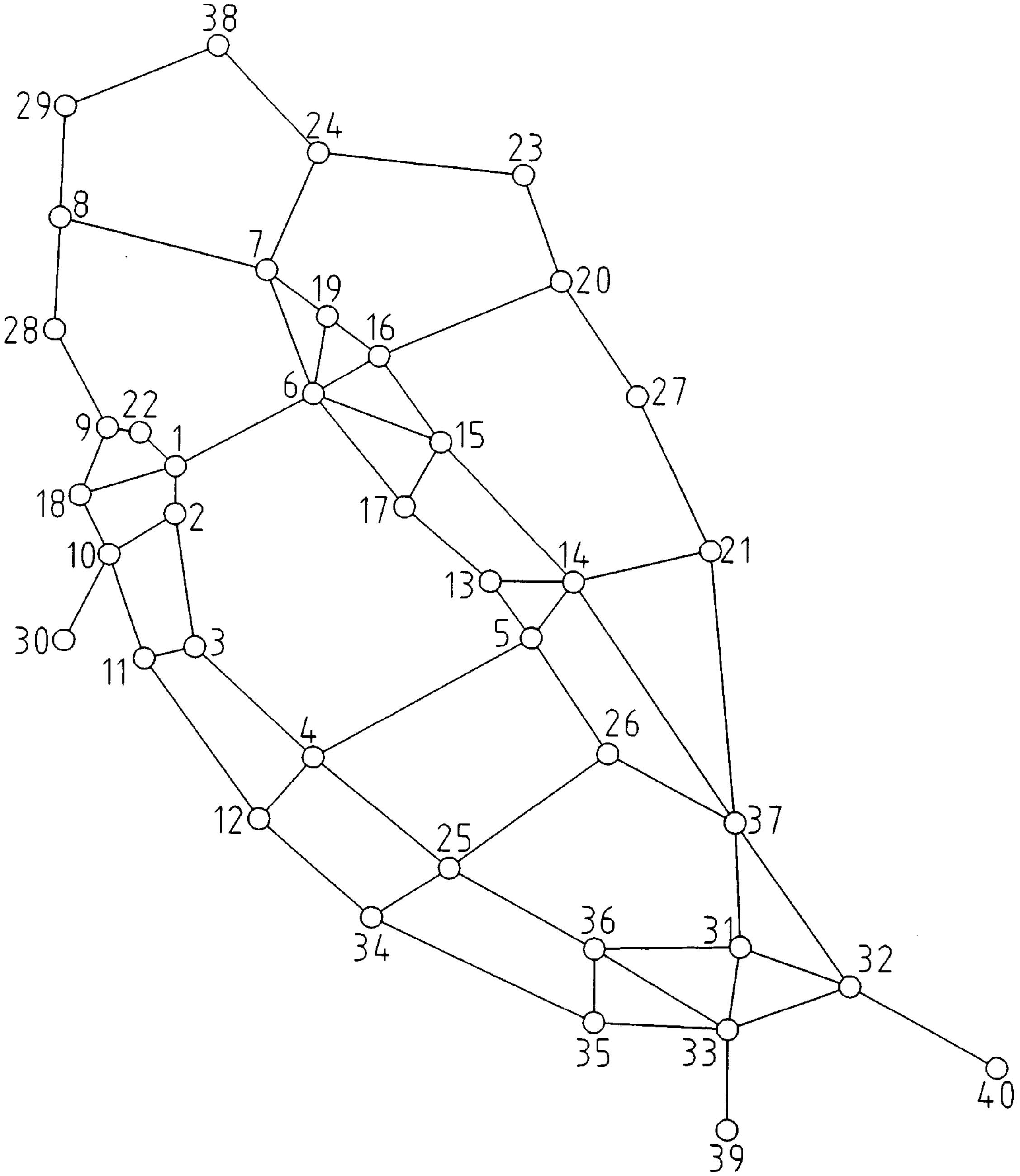


Figure 5 Abstracted road network

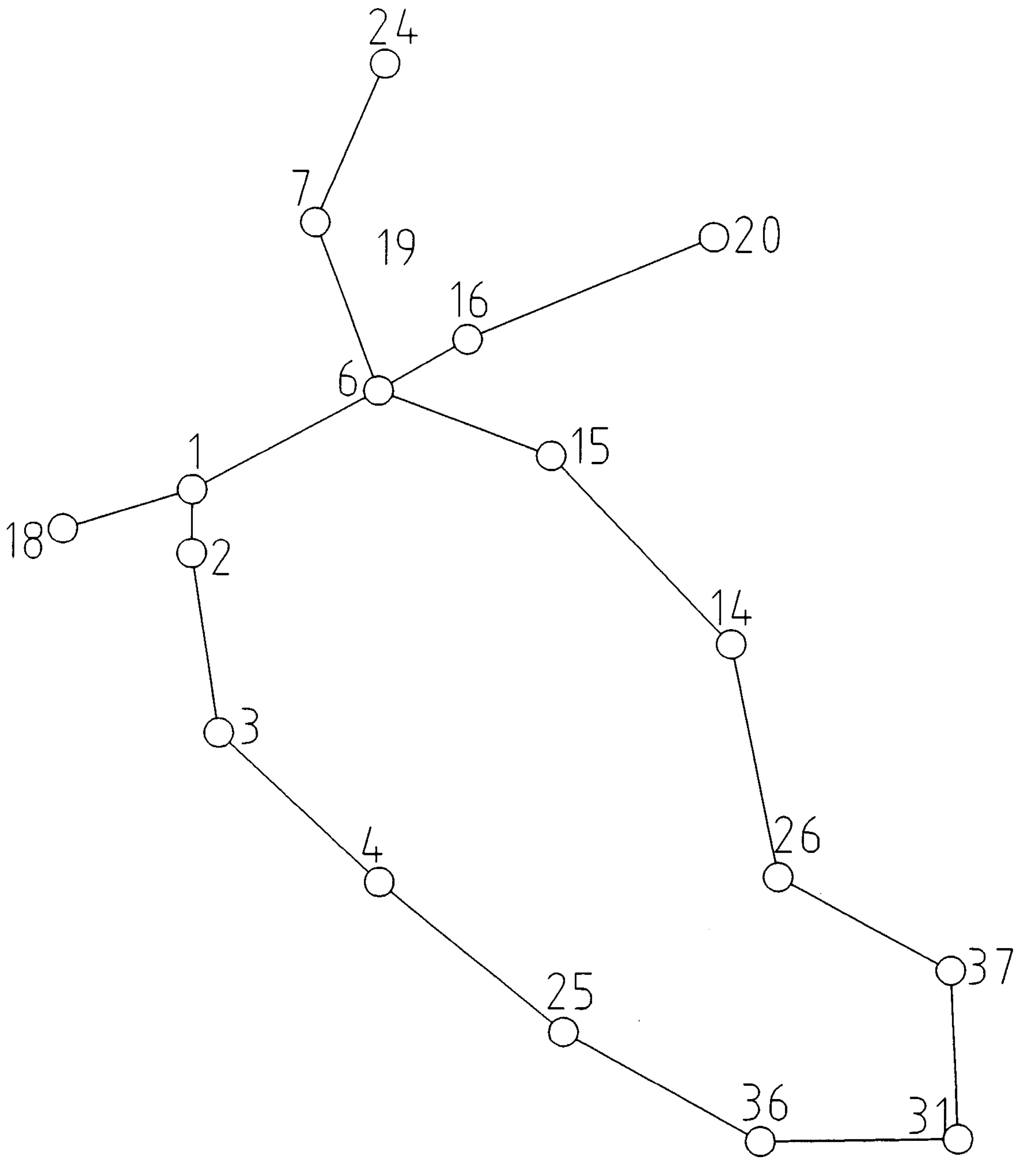


Figure 6 Abstracted public transport network

3.3 Transportation Model

For a detailed presentation of sub-models 3, 4, 5, 6 and 7 we refer to (Hamerslag, 1994). The theoretical foundation for the model is a micro-economic theory under money and time constraints (Hamerslag, van Berkum and Replogle, 1994). We applied these models to the abstracted road network of the San Francisco Bay Area. The resulting estimated trip ends and estimated origin-destination (OD)-matrix are enclosed in appendices C and D respectively.

The zone-aggregated estimates of concentrations of dwelling and employment according to this model have been compared with evening commuter data from surveys at certain points in the San Francisco Bay Area (Metropolitan Transportation Commission, 1993). Figures 7 and 8 compare the surveyed data with our estimates. This comparison of our estimates for employment and working population with surveyed commuter data provides a validation of the model outcomes.

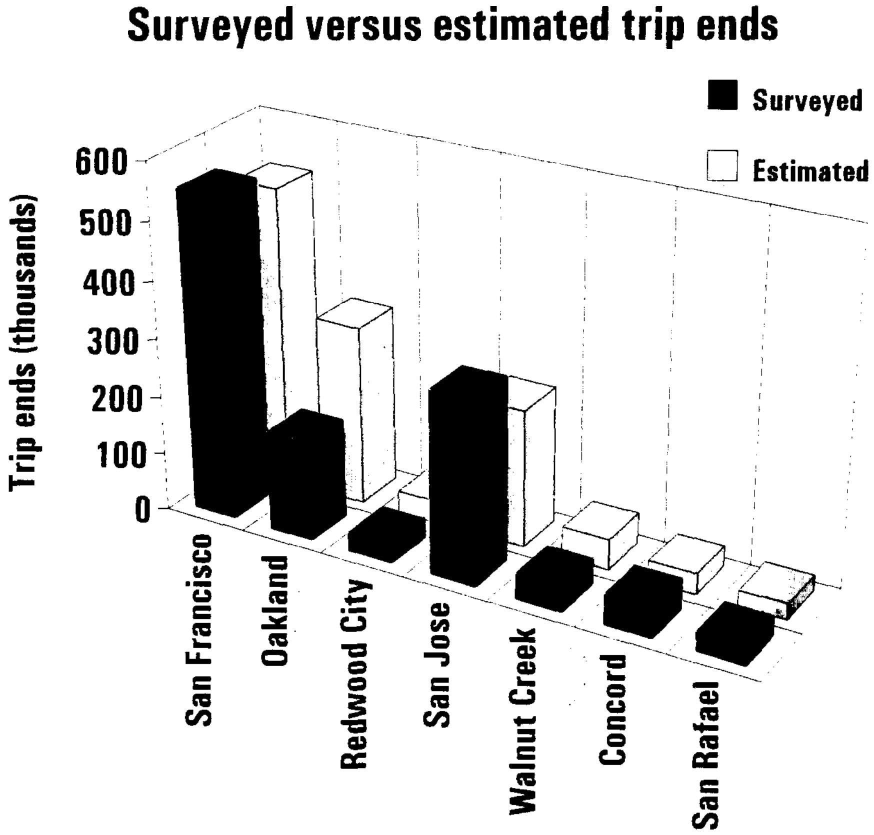


Figure 7 Surveyed and estimated trip ends

Aggregated zone	**Surveyed commuters**	**Estimated employment T_{i+}**	**Surveyed / estimated**
San Francisco	555,447	514,078	1.08
Oakland	174,116	315,350	0.56
Redwood City	36,862	39,117	0.94
San Jose	319,397	234,039	1.36
Walnut Creek	47,065	55,843	0.84
Concord	55,514	37,535	1.48
San Rafael	35,919	28,358	1.27
Total	1,224,320	1,224,320	1.00

Figure 8 Surveyed and estimated trip ends

3.4 Car and Public Transport Assignment

The previous steps estimate the expected number of trip-ends, in the form of an origin-destination (OD)-matrix. Sub-model 8, Car Assignment, and sub-model 9, Public Transport Assignment, use this OD-matrix to estimate traffic flows in the road network, according to shortest routes. This computational process is called ‘traffic assignment’.

The amount of road traffic q_a assigned to road link a depends on the travel resistance Z_a of that road link, which is assumed to be a function of the actual traffic load q_a on that link. The resistance is expressed in units of time, and expresses an average of different sacrifices, such as travel time and costs, which are subjective. Therefore, Z_a is sometimes called generalized time. Estimation of Z_a requires an iterative computation, simultaneously solving the distribution of link traffic flows in the network. We use a stochastic equilibrium assignment method (Ortúzar and Willumsen, 1990). Each iteration step i consists of the following steps:

1. Determine the operational travel time $Z_a[i]$ on each link by randomizing the travel time $Z_a[i-1]$ obtained in the previous iteration step

$$Z_a[i] = \begin{cases} Z_a[i-1] + c\, X_{a,i} \sqrt{Z_a[i-1]} & \text{for } i = 2,3,\dots \\ Z_{a,0} & \text{for } \quad i=1 \end{cases} \tag{1}$$

   where index a denotes the road link, c is an empirical coefficient with a value between 0.2 and 0.8 (default 0.5) indicating the level of uncertainty and $X_{a,i}$ is a random variable with a normal probability distribution. In the initial iteration step $(i = 1)$, the travel time equals the free-flow travel time $Z_{a,0}$, i.e., the travel time if $q_a = 0$.

2. The randomized link travel resistances $Z_a[i]$ are used to calculate the shortest route paths for each of the origin-destination pairs specified in the OD-matrix. Each iteration step i thus gives a different shortest route tree B_i which is kept for further calculation.

3. The vehicle traffic specified by the OD-matrix is assigned to the shortest-route tree. This results in an estimate of the traffic flow on each link a, denoted as $q_a^+[i]$.

4. To take into account that in general travelers do not have perfect and complete knowledge of all link resistances and that travelers may have different cost functions for generalized travel time, only a partion α of all traffic will choose the route with the shortest generalized time delay, while portion $1 - \alpha$ is assumed to take the previously obtained fastest route which is the fastest from a subjective point of view for these travelers.

So, in the i-th iteration step the traffic flow on road link ***a*** is given by the linear combination

$$q_a[i] = \begin{cases} (1 - \alpha) q_a[i-1] + \alpha q_a^{*}[i] & \text{for } i = 2,3,\ldots \\ q_a^{*}[1] & \text{for } i = 1 \end{cases} \qquad (2)$$

5. In the last phase of each iteration step, the travel time Z_a on freeway link ***a*** is estimated from the actual traffic load on that link using the following time-delay function (see for instance Ortúzar and Willumsen, 1990)

$$Z_a[i] = Z_{a,0} \left\{ 1 + k \left(\frac{q_a[i]}{c_a} \right)^{b} \right\} \qquad (3)$$

where q_a and c_a are the actual and the steady flow (k = 1) or practical ($k = 0.15$) capacity of link a, respectively, expressed in vehicles per hour and $Z_{a,0}$ is the link travel tune in the unloaded (free-flow) situation. Typically, b is in the range of 2 to 6. The maximum traffic load c_a is determined by the network specifications (number of lanes, etc.).

This iteration scheme is performed with level of uncertainty α = 0.2, exponent $b = 4.5$ and constant k = 1 until the stop criterium (20 iterations) has been reached.

Figure 9 illustrates the estimates of road traffic flows, found according to this scheme. The different hatches represent q_a / c_a, i.e., the amount of vehicle traffic traveling on a road link relative to the capacity of that link and provide estimates of link travel times. A ratio of q_a / c_a is 0.85 or higher indicates congested traffic. The estimated road link flows and road link travel times, resulting from sub-model 10, are enclosed in appendix E.

Detailed validation of our estimated road link flows with real traffic measurements could not yet been done. Rough comparison with the traffic situation on the freeways in the San Francisco Bay Area during average peak hours indicate that the estimations are realistic. For our purpose, i.e., creating a sufficiently realistic traffic situation to evaluate the performance of the probe vehicle concept for collecting traffic messages, this verification is believed to be adequate, as it pictures an average traffic situation in the Bay Area.

We used a static traffic assignment, so the traffic situation is a steady state during the whole evening peak hour. This static point of reference may seem slightly contradictory to the dynamic aspects of traffic flows in practice. As a refinement, the applications of a dynamic traffic assignment algorithm would give better insight in time varying traffic flow fluctuations. This was not done since this study concentrates on the possibilities of dynamic traffic data collection by probe vehicles rather than on processing dynamic traffic data into useful traffic information. Moreover, the advantage of using a static traffic situation as point of reference is that communication aspects can be studied more thoroughly, so better insight can be gained into their effects on the throughput of traffic messages.

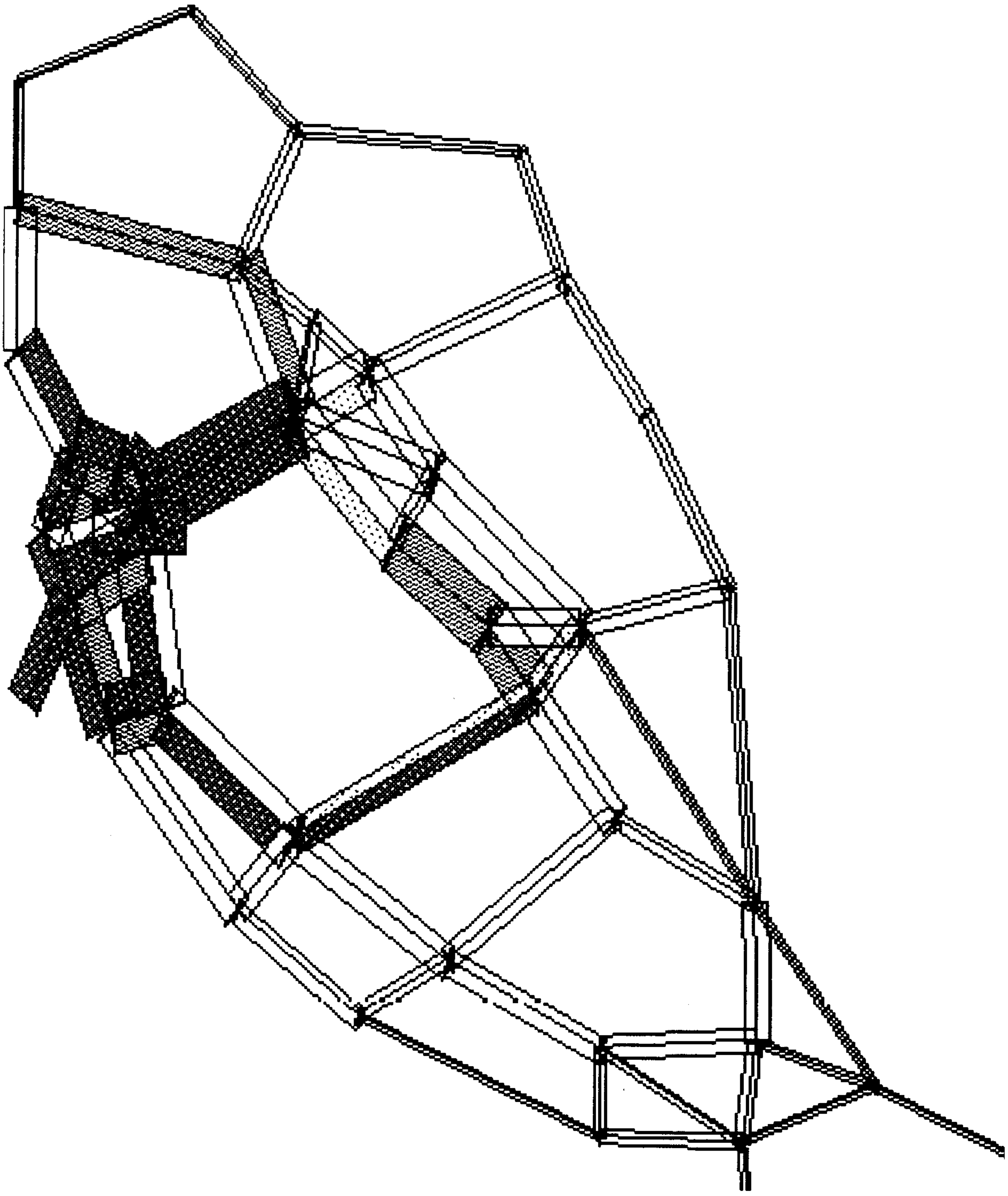


Figure 9 Screen dump of computed road traffic flows during the evening rush hour on the freeway network in the San Francisco Bay Area

3.5 Generation of Traffic Messages

In sub-models 11 (analysis) and 12 (simulation), the fleet of probe vehicles is taken as a certain fraction ζ ($0 < \zeta < 1$) of all vehicles. Probes are assumed to be equipped with positioning and radio communication equipment. By means of simulation or computation, the effectiveness of the probe vehicle concept is analyzed. For our study, the probe vehicles are assumed to randomly generate traffic messages according to the slotted ALOHA transmission scheme (Abramson, 1977; Walrand, 1991). These messages contain the position of the probe vehicle and the link travel time experienced. In slotted ALOHA, mutual interference between messages transmitted from different probes can occur. Messages transmitted in the vicinity of a base station are more likely to 'capture' its receiver than other messages. To study this, the effect of distance on the distribution of traffic messages received by a listening base station is obtained by simulation and also by numerical evaluation of an analytical model. The latter will be called the analytical approach in the following sections.

The simulation generates probe vehicles sequentially, and it follows probes driving along the calculated shortest routes from their specific origin to their specific destination. Each probe transmits on average once every T seconds, choosing a random time slot. For every transmitted message we store its time slot and, after all probes have been generated and have reached their destinations, the data base with time stamps is sorted on time slot. Subsequently for each transmitted message, its (area-mean) received power is calculated from a path loss model, as well as the (area-mean) interference power from other messages in the same time slot. To include the effect of fading, a random experiment decides whether the message is received successfully at a base station. The probability of successful reception is in agreement with theoretical models to be described in the next section. This process is repeated for all base stations.

In the analysis, we focus on one particular road link a of the freeway with a traffic flow of q_a vehicles per hour and average travel time of Z_a minutes. Using Little's Law, the expected number of vehicles present on road link a is $q_a Z_a$. We call this the link traffic density. At this point we assume that the travel time is equal to Z_a, thus we ignore any subjective aspects incorporated in Z_a. For a penetration rate ζ ($0 < \zeta < 1$), the expected number of ***probe*** vehicles that are present in segment a is

$$\zeta \, q_a \, Z_a \qquad (4)$$

Each probe transmits on average once every T seconds, choosing a random time slot. Since the number of vehicles is large, the message transmission process becomes Poissonian. The mean number of messages per time slot from segment a is

$$G(a) = \frac{\zeta \, q_a \, Z_a}{T f_s} \qquad (5)$$

where the sampling rate f_s denotes the number of slots preserved for probe messages per second. According to the road traffic assignment model, the traffic density only changes at junctions, on-off ramps or intersections, so the road network computations have been performed with relatively large links. The propagation characteristics can however greatly vary over the length of such a link. Therefore, the analytical evaluation of the radio network considers shorter road segments, as sub-segments of the longer road links.

3.6 Calculation of Spatial Throughput

A detailed analytical discussion of the calculation of spatial throughput (sub-models 13 and 14) can be found in appendix A. Here we limit ourselves to a short synopsis.

The traffic messages from the probe vehicles are transmitted with a transmit power of P_i. When these messages arrive at a listening base station A they have experienced a power loss. An appropriate empirical model (Egli, 1957) gives an area-mean power $\bar{p}_{A,i}$

$$\bar{p}_{A,i} = G_A \, P_i \, h_i^2 \, h_A^2 \, r_i^{-4} \left(\frac{40 \text{ MHz}}{f_c} \right)^2 \qquad (6)$$

where G_A is the antenna gain pattern of receiving base station A, h_i is the antenna height at probe i, h_A is the base station antenna height, r_i is the distance from transmitting probe vehicle to receiving base station **and** f_c is the carrier frequency.
Here, area-mean power is defmed as the received power, averaged for an area of several tens of meters. It is generally accepted that the received power is further subject to shadowing and multipath fading. In this report, we ignore the effect of shadowing. Because of **Rayleigh** fading, the received power $p_{A,i}$ is an exponential random variable with mean $\bar{p}_{A,i}$.

A transmitted traffic message will only be received correctly at base station A **if** the received power $p_{A,i}$ is above a certain threshold. For an interference-free situation this probability of successful reception P_{NA} depends on the area-mean power $\bar{p}_{A,i}$ and the receiver noise floor, viz (Lirmartz, 1993)

$$P_{NA} = \mathrm{P}\left(p_{A,i} > z F k T_0 r_b\right) = \exp \left\{ - \frac{z \, F \, k \, T_0 \, r_b}{\bar{p}_{A,i}} \right\} \qquad (7)$$

where z is the receiver threshold, i.e., the signal-to-noise ratio required for reliable communication, F is the man-made noise factor, kT_0 is a noise constant and r_b is the channel bit rate.

In slotted ALOHA, several traffic messages can be transmitted at the same time. This leads to mutual interference between messages. The probability that a traffic message from probe i, transmitted from road segment a, at a distance r_i from receiving base station A will be successfully received, can be written as the product of the probability of successful reception without interference, P_{NA}, and factor $\mathrm{P}(A_i | r_i)$ accounting for the interfering traffic messages transmitted from all other road segments in the same time slot. We assume that this probability is equal and independent for all probes at segment a.

In our simulation approach, we continuously generate interfering probe vehicles. For N interferers, at distance $r_1, \ldots, r_N, \ldots$ the probability of successful reception of a test package from probe vehicle i is

$$P(A_i \mid r_i, r_1, .., r_N) = \prod_{k=1}^{N} \frac{r_k^4}{r_k^4 + z r_i^4} \qquad \textbf{(8)}$$

We further assume that the joint arrival process of interfering probe messages is a Poisson process.

In our analytical approach, the probability of successful reception $P(A_a \mid r_a)$ of a message from segment a in a noise-free environment can be shown (see appendix E) to be

$$P(A_a \mid r_a) = \exp\left\{ - \sum_{\text{all links } i} \frac{z r_a^4}{z r_a^4 + r_i^4} G(i) \right\} \qquad (9)$$

where r_a is the distance between road segment ***a*** and base station ***A*** and the parameter ***i*** indicates dummy variable in the sum over all segments that cause interference. ***G(i)*** is the mean number of traffic messages per time slot transmitted by the probe vehicles on road segment ***i,*** computed in sub-model 11. So the successful throughput, expressed in messages per unit of time from road segment ***a*** becomes

$$S(a) = G(a)\, P_{NA}\, P(A_a \mid r_a) \qquad \textbf{(10)}$$

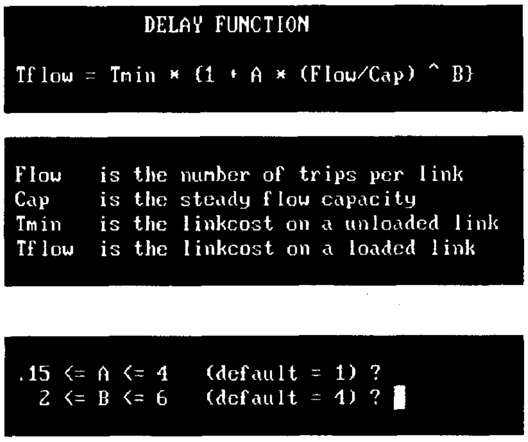
In (Linnartz and Westerman, 1994B) and in appendix A the probability of successful reception is given, when more base stations are listening to the channel.

4 Case Study: Road Traffic and Message Traffic in the San Francisco Bay Area

We developed a computer tool called PROMOT (PRObe vehicle concept for MOnitoring road Traffic). This model consists of two computer tools, a simulation and an analysis, for investigating the performance of the random acces radio scheme for collecting real-time road traffic data. These programs have been applied to the San Francisco Bay Area. The specifications of the model and these tools have been given in chapter 3. In this chapter the results will be presented and discussed. The figures in this chapter are black and white screen dumps. We advice the interested reader to run the PROMOT program if colour graphics are desired.

4.1 Input of System Parameters

In the first phase of the program, the link traffic flows q_a and link travel times Z_a are computed iteratively as described in section 3.4. For these iterations, a delay and a cost function are used. The delay function (3) estimates the link travel times from earlier computed link flows and the cost function represents the non-rational human choice caused by uncertain and incomplete information and so randomizes the estimated travel times in (1). According to these randomized travel times, car drivers choose the shortest route from origin to destination. The delay and the cost function contain several empirical constants. These constants have default values and can be adjusted if desired. Figures 10 and 11 show the input screens that allow these constants to be changed in the computer program.



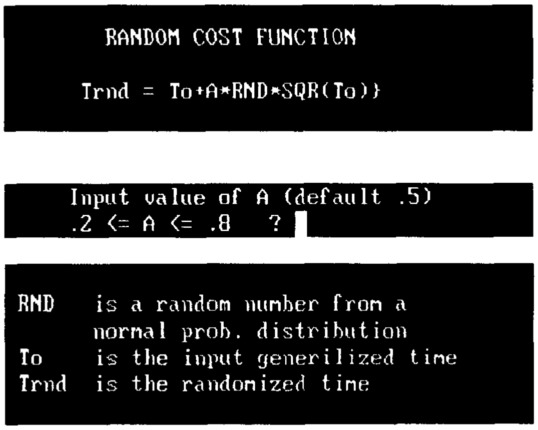
```
          DELAY FUNCTION

Tflow = Tmin * (1 + A * (Flow/Cap) ^ B}
```

```
Flow   is the number of trips per link
Cap    is the steady flow capacity
Tmin   is the linkcost on a unloaded link
Tflow  is the linkcost on a loaded link
```

```
.15 <= A <= 4   (default = 1) ?
  2 <= B <= 6   (default = 4) ?
```

Figure 10 Input screen: delay function of the stochastic equilibrium assignment



```
        RANDOM COST FUNCTION

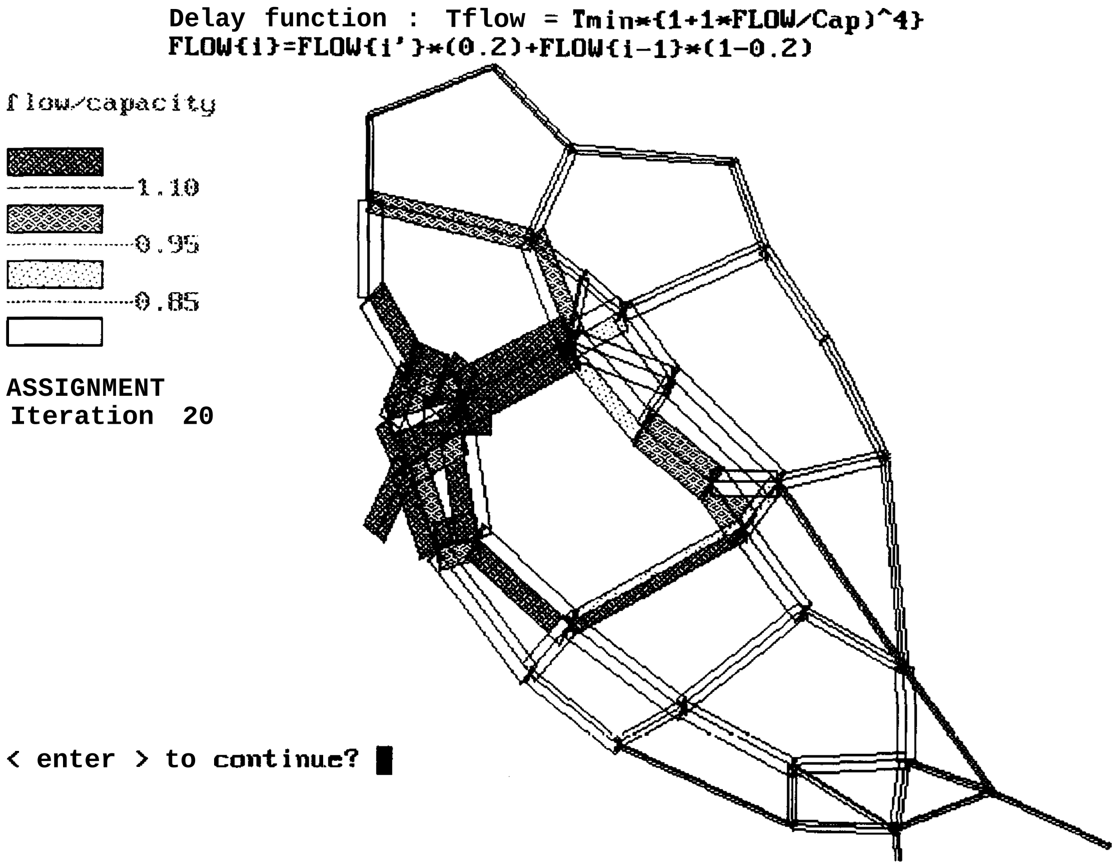
      Trnd = To+A*RND*SQR(To))
```

```
    Input value of A (default .5)
    .2 <= A <= .8   ?
```

```
RND    is a random number from a
       normal prob. distribution
To     is the input generilized time
Trnd   is the randomized time
```

Figure 11 Input screen: random cost function of stochastic equilibrium assignment

Figure 12 is a screen dump that depicts the computed road link flows and link travel times using default values of delay and cost function. The thickness of the links on the screen represents the expected number of vehicles $q_a Z_a$ that are present on that link. The hatch of the links denotes the travel time (delay) Z_a on that link according to the legend given on the left hand side of figure 12.

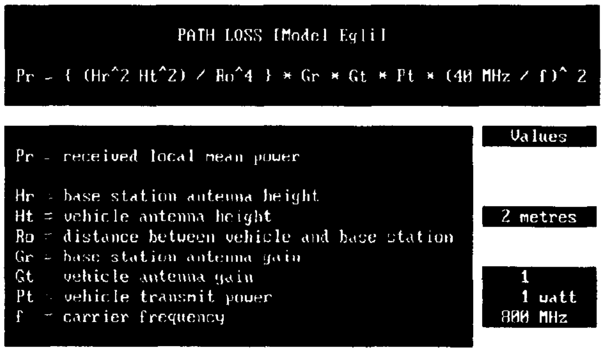


```
Delay function :  Tflow = Tmin*{1+1*FLOW/Cap)^4}
FLOW{i}=FLOW{i'}*(0.2)+FLOW{i-1}*(1-0.2)
```

```
ASSIGNMENT
Iteration  20

< enter > to continue?
```

Figure 12 Computed road traffic flows during the evening rush hour on the freeway network in the San Francisco Oakland - San Jose Bay Area



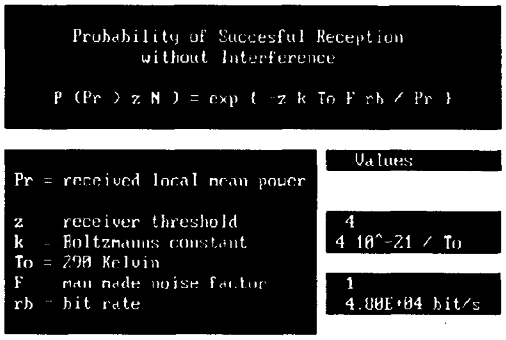
```
              PATH LOSS [Model Egli]

Pr - { (Hr^2 Ht^2) / Ro^4 } * Gr * Gt * Pt * (40 MHz / f)^ 2

                                                  Values
Pr - received local mean power

Hr - base station antenna height
Ht = vehicle antenna height                      2 metres
Ro = distance between vehicle and base station
Gr - base station antenna gain
Gt   vehicle antenna gain                          1
Pt - vehicle transmit power                        1 watt
f  - carrier frequency                           800 MHz
```

Figure 13 Input screen: path loss model



```
   Probability of Succesful Reception
         without Interference

 P (Pr ) z N ) = exp { -z k To F rb / Pr }

                                 Values
Pr = received local mean power

z    receiver threshold           4
k  - Boltzmanns constant         4 10^-21 / To
To = 290 Kelvin
F    man made noise factor        1
rb - bit rate                     4.00E+04 bit/s
```

Figure 14 Input screen: calculating the probability of succesful reception

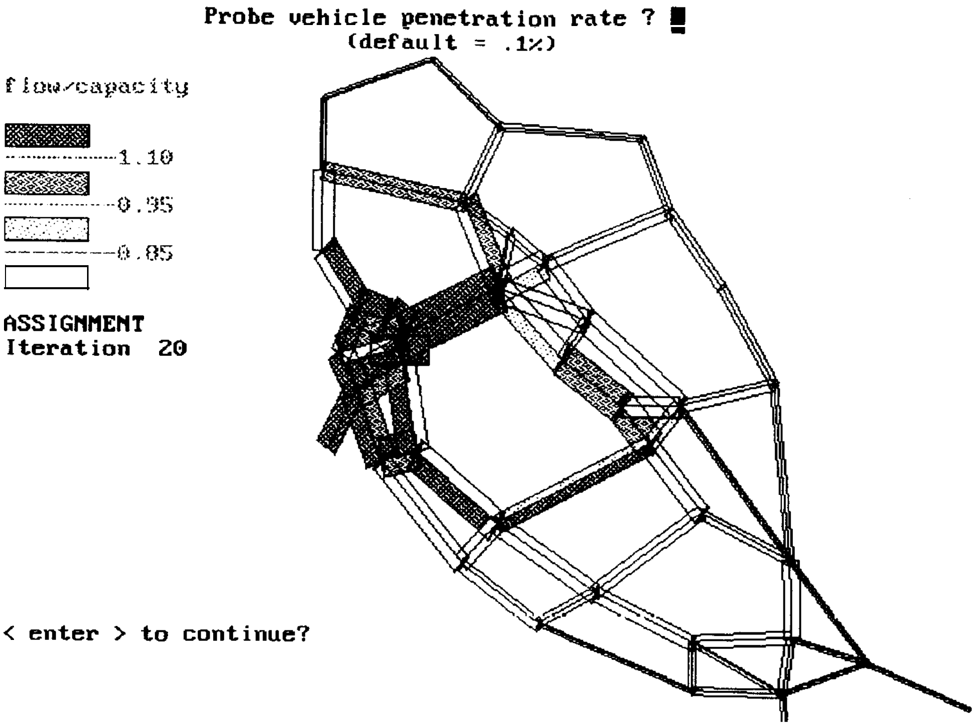
A certain percentage ζ of the assigned vehicles are designated as probe vehicles and regularly transmit traffic messages according to the ALOHA transmission scheme. The default parameters correspond a packet radio system similar to the IS-54 standards for telephony in the 800 MHz UHF cellular band, but these can be modified if desired. Figures 13 and 14 show the input screens for specifying parameters in the path loss model and in the model for calculating the probability of successful reception. Default values correspond to Egli's path loss model (Egli, 1957). A theoretical discussion of these models is given in appendix A.

Each probe transmits, on the average, once every T seconds, choosing a random time slot. The number of time slots per second that are reserved for probe vehicle messages is denoted as f_s. These three parameters ζ, T and f_s are the main variables that determine the message traffic intensity on the radio channel. Our default value off, = 18 slots per second corresponds to our design for a single-channel IVHS communication architecture (Linnartz, 1994). This design also allows other services to be offered through 30 kHz of radio bandwidth. Our experience is that a higher 'sampling' rate ($f_s >> 18$) may claim too much of the available spectrum at the expense of other services. A lower sampling rate appears to significantly decrease the efficiency of the probe vehicle concept. This leaves the parameters ζ and T to be varied in the transmission scheme. Our earlier analysis showed that in the relevant expressions for throughput, the ratio ζ/T occurs as the most important parameter. If the probe penetration rate is sufficiently large, only the average number of messages per link per unit of time matters. At large penetration rates, the interval between transmissions can be reduced to avoid excessive message collisions, which optimizes the number of received messages per unit of time. If, on the other hand, the penetration rate is small, one may theoretically compensate this by choosing T small. However, we do not think that it is useful to take T much smaller than 60 seconds, as a base station may otherwise frequently receive reports from the same vehicle, containing no new information.

After the traffic flow has been calculated, the spatial throughput of messages from the probes is calculated. This can be done either by means of simulation or by numerical evaluation of the analytical expressions. The theory behind both methods has been described in chapter 3. The next two paragraphs illustrate the use of the PROMOT computer model. We encourage the reader to run this program while reading.

4.2 Numerical Evaluation of the Analytical Tool

Figure 15 shows the screen to modify the parameters ζ, T and f_s in the analytical program. The traffic flows are the same as those in figure 12. Figure 16 applies for default transmission parameters $\zeta = 0.1\%$, T = 60 seconds and $f_s = 18$ time slots per seconds. In figure 16, the thickness of the links denotes the expected number of traffic messages $G(a)$ transmitted from that link. This is proportional to the amount of link vehicle traffic and to the link travel time. The hatch of the links in figure 16 represents the number of vehicles that are present on that link. A legend is available on the left hand side of figure 16 (Please mark the differences in interpretation of thickness and hatches between figure 15 and figure 16 !). In the screen of figure 16, listening base stations can be located by moving the cursor. The square indicates the current location of the cursor and the X, Y-coordinate of this location is shown in the bottom-left side of the screen. By pressing the < + > key, a base station can be placed at the current cursor location.

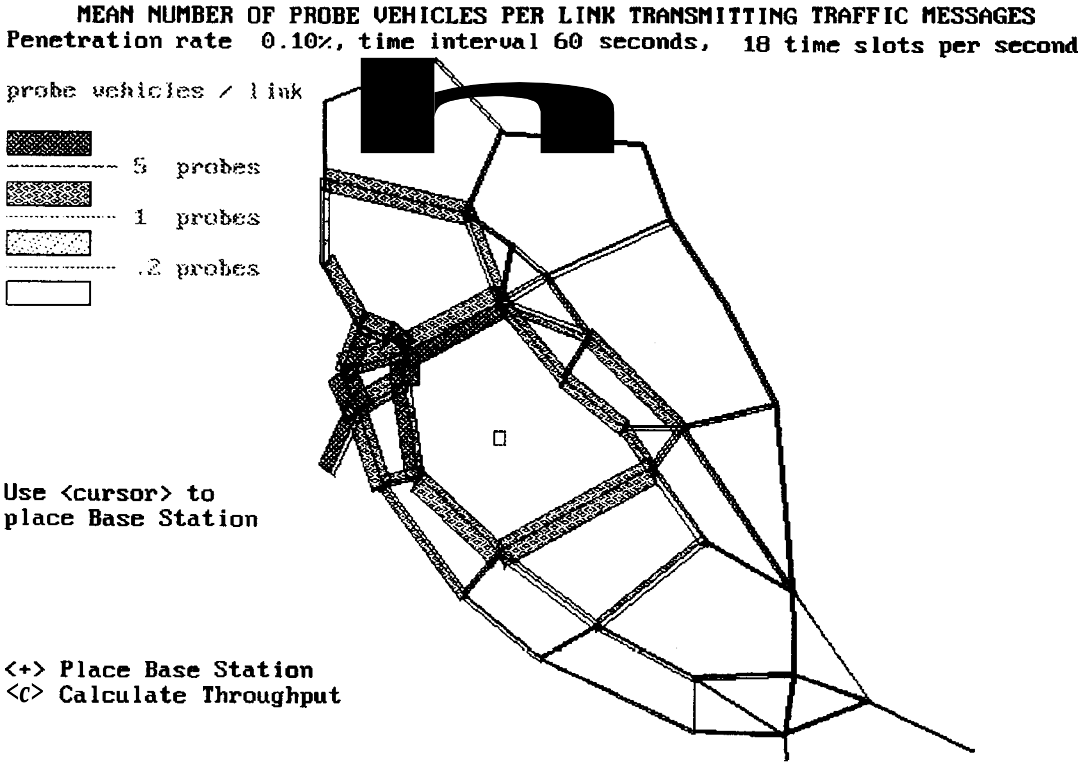


```
Probe vehicle penetration rate ? ▮
          (default = .1%)

ASSIGNMENT
Iteration  20

< enter > to continue?
```

Figure 15 Screen to enter ζ, T and f_s
(Background: computed road traffic flows)



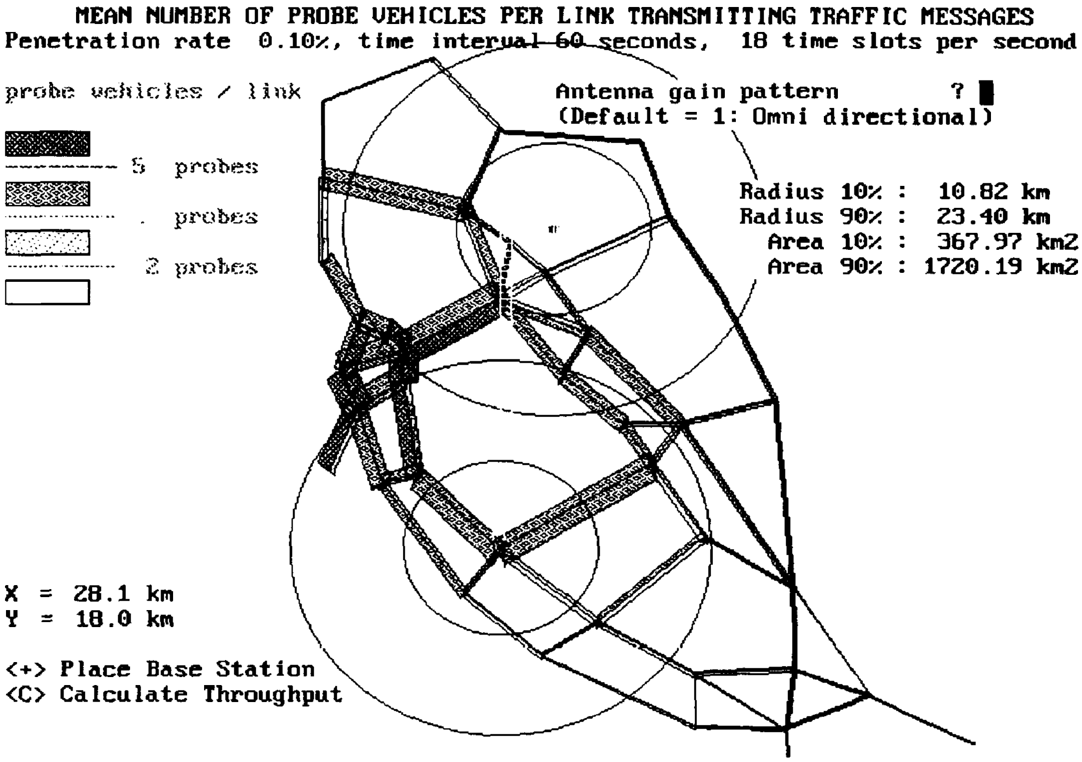
```
    MEAN NUMBER OF PROBE VEHICLES PER LINK TRANSMITTING TRAFFIC MESSAGES
Penetration rate  0.10%, time interval 60 seconds,  18 time slots per second

Use <cursor> to
place Base Station

<+> Place Base Station
<C> Calculate Throughput
```

Figure 16 Mean number of probe vehicles per road link
using default transmission parameters

The antenna height of the base station and the antenna gain pattern can be specified next. The default base station antenna height is h_r = 100 meters. Only an omni-directional antenna gain pattern is available in the program now (in figure 17). Other patterns can included if required, but computation time may increase substantially. The two circles around the base station indicate the area from where, in an interference-free time slot (no collision), the probability of successful reception is .9 (inner circle) and .1 (outer circle). That is, it expresses the effect of noise, path loss and channel fading. The radius of both circles and the size of the surface area enclosed by them is shown in the upper-right hand comer of the screen. After the base stations have been placed, the throughput for each road link at the different base stations will be calculated by pressing the <C> key.



```
MEAN NUMBER OF PROBE VEHICLES PER LINK TRANSMITTING TRAFFIC MESSAGES
Penetration rate  0.10%, time interval 60 seconds,  18 time slots per second

Antenna gain pattern        ?
(Default = 1: Omni directional)

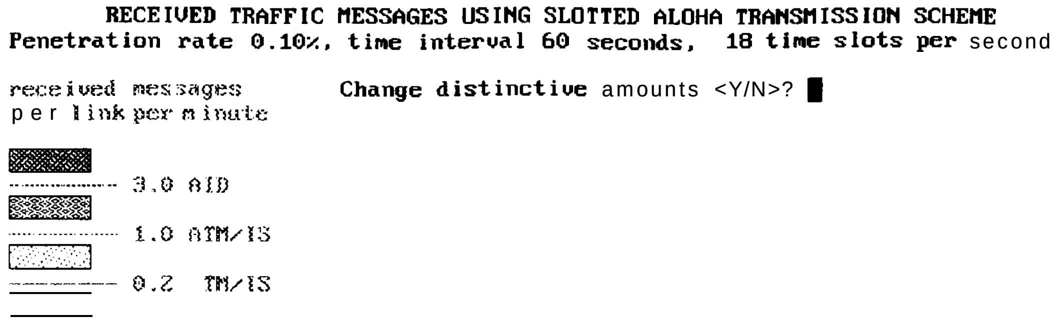
Radius 10% :   10.82 km
Radius 90% :   23.40 km
  Area 10% :  367.97 km2
  Area 90% : 1720.19 km2

X  =  28.1 km
Y  =  18.0 km

<+> Place Base Station
<C> Calculate Throughput
```

Figure 17 Placing a base station:
omni-directional antenna gain pattern

At this stage, the program has sufficient information to compute link throughput. Results are presented in different colour, indicating wether Automatic Incident Detection (AID), Advanced Traffic Management / Traveler Information Systems (ATM/IS) or (traditional) Traffic Management / Traveler Information Systems (TMIS) can be performed with sufficient information on the road traffic status. In order to present these results graphically, it first asks criteria for the number of road traffic samples per road link per minute required to perform reliable IVHS services. The program user can set thresholds for AID, ATMIS and (traditional) TMIS. As seen on the screen in figure 18, we have provisionally set the requirements to 3 messages per link per minute for AID, 5 messages per link per 5 minutes for ATM/IS and 1 message per link per 5 minutes for (traditional) TM/IS.



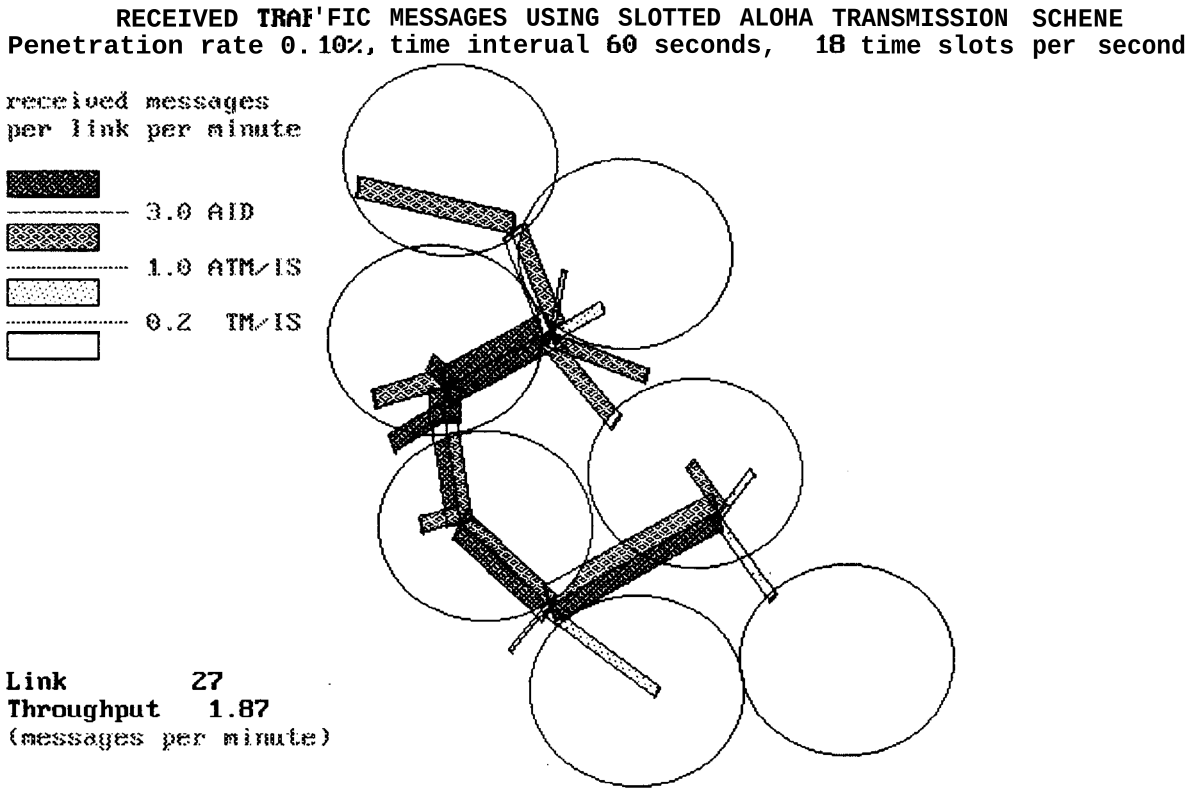
RECEIVED TRAFFIC MESSAGES USING SLOTTED ALOHA TRANSMISSION SCHEME
Penetration rate 0.10%, time interval 60 seconds, 18 time slots per second

received messages per link per minute   Change distinctive amounts <Y/N>?

3.0 AID
1.0 ATM/IS
0.2 TM/IS

Figure 18 Computing the spatial throughput per road link expressed in received traffic messages per road link

In this way, the hatches give some indication of how well AID and ATM/IS perform. However, the number of probe messages per link per minute required to perform reliable ATM/IS, is to be investigated further. We speculate that the number of messages required per link may depend on the expected vehicle density and velocity, rather than being a constant number, as is assumed here.



RECEIVED TRAFFIC MESSAGES USING SLOTTED ALOHA TRANSMISSION SCHENE
Penetration rate 0.10%, time interual 60 seconds, 18 time slots per second

received messages per link per minute

3.0 AID
1.0 ATM/IS
0.2 TM/IS

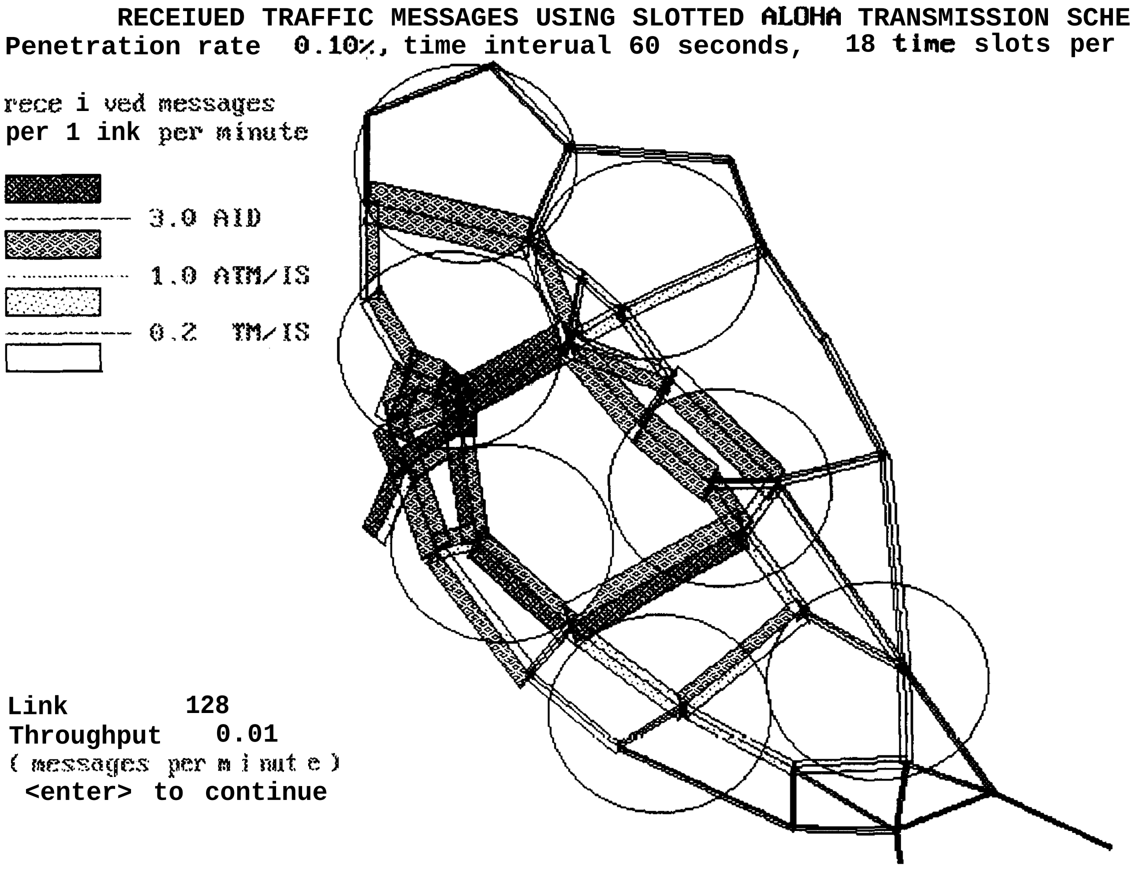
Link 27
Throughput 1.87
(messages per minute)

Figure 19 Computing the spatial throughput per road link expressed in received traffic messages per road link

The throughput per road link (expressed in received traffic messages per minute from that road link) is calculated by taking into account the possibility that one traffic message can be received by more than one base station (for site diversity: see Appendix A). The analysis considers only the three nearest base stations for each link, as farther base station contribute little to the throughput.

For each road link, the distance to each of its three nearest base stations is calculated. Using the expressions given in section 3.6 and Appendix A, for each base station, the number of messages received from that specific link per time slot is determined taking into account site diversity. These results are written to an output file. So, for each road link, the expected number of traffic messages received per minute, i.e., in f_s times 60 time slots, is pictured in figure 19.

At this stage, the throughput is estimated for all road links. The results are pictured in figure 20, using all default values, specified numbers and locations of base stations, etc. The thickness of the links in figure 20 denotes the number of transmitted messages per minute from that link. The hatch of the links in figure 20 represents the number of successfully received traffic messages per minute. A legend is available on the left hand side of the screen.



```
        RECEIUED TRAFFIC MESSAGES USING SLOTTED ALOHA TRANSMISSION SCHEME
Penetration rate  0.10%, time interual 60 seconds,  18 time slots per second

Link        128
Throughput    0.01
( messages per minute )
 <enter> to continue
```

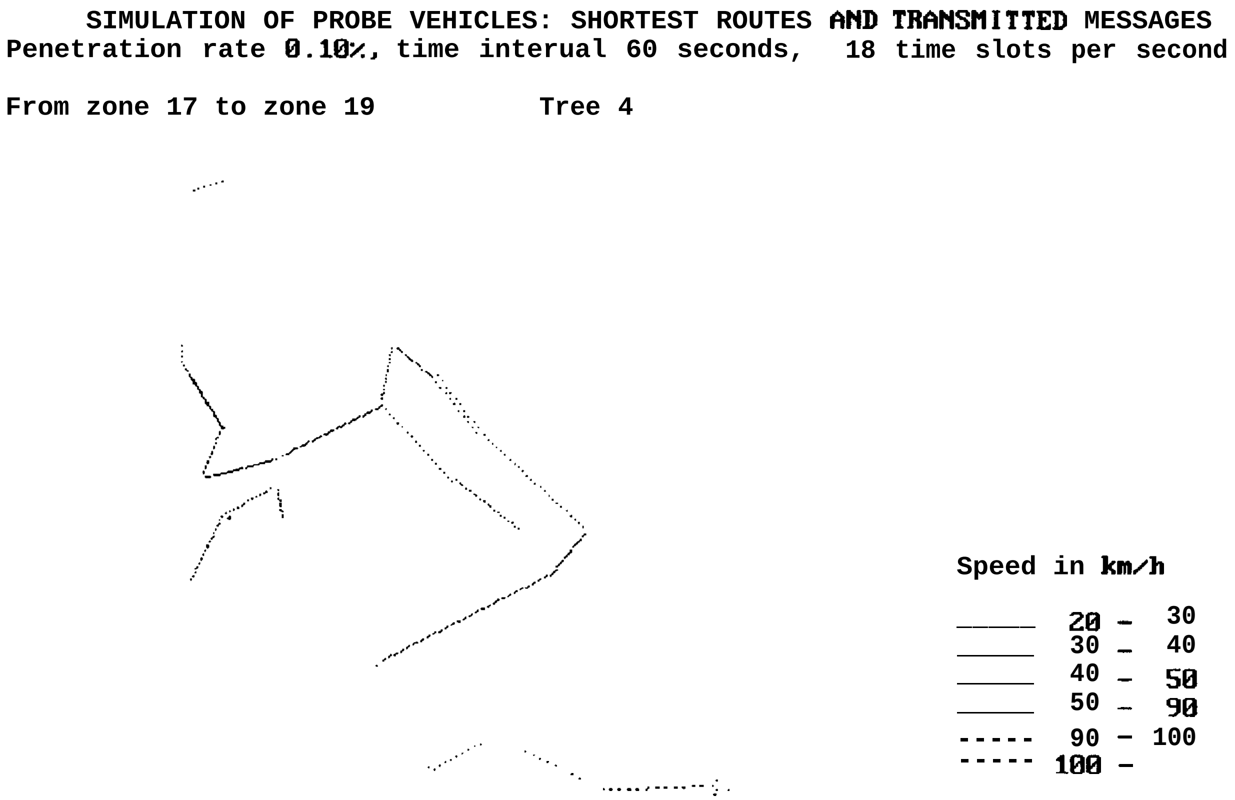
Figure 20 Computed spatial throughput per road link expressed in received traffic messages per minute

4.3 Simulation

In the simulation software, a menu is available to modify the parameters ζ, T and f_s. After the user specifies the probe vehicle penetration rate ζ, the number of probe vehicles on the road network is calculated.
The screen shows:

- the expected number of vehicles from origin i to destination j,
- the expected number of probe vehicles from origin i to destination j,
- the cumulative number of vehicles, and
- the cumulative number of probe vehicles.

After specifying the number of time slots per second reserved for uplink probe vehicle transmissions f_s and the mean time interval between successive transmissions T, the trajectory of all probes is simulated sequentially. A probe travels along (one of the) (subjectively) shortest route(s) from origin i to destination j experiencing a set of link travel times Z_a and it transmits a traffic message every T seconds. Figure 21 illustrates a snapshot of this process.



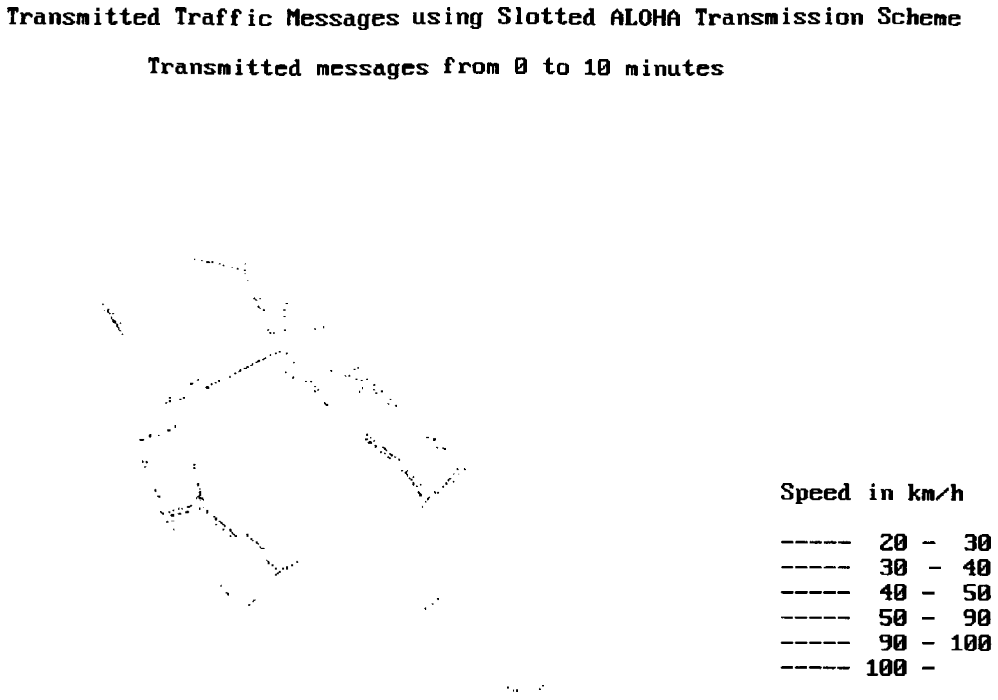
```
     SIMULATION OF PROBE VEHICLES: SHORTEST ROUTES AND TRANSMITTED MESSAGES
Penetration rate 0.10%, time interual 60 seconds,  18 time slots per second

From zone 17 to zone 19          Tree 4

                                                   Speed in km/h

                                                   _____   20 -  30
                                                   _____   30 -  40
                                                   _____   40 -  50
                                                   _____   50 -  90
                                                   -----   90 - 100
                                                   -----  100 -
```

Figure 21 Simulated probe vehicles travelling along the shortest routes in the network

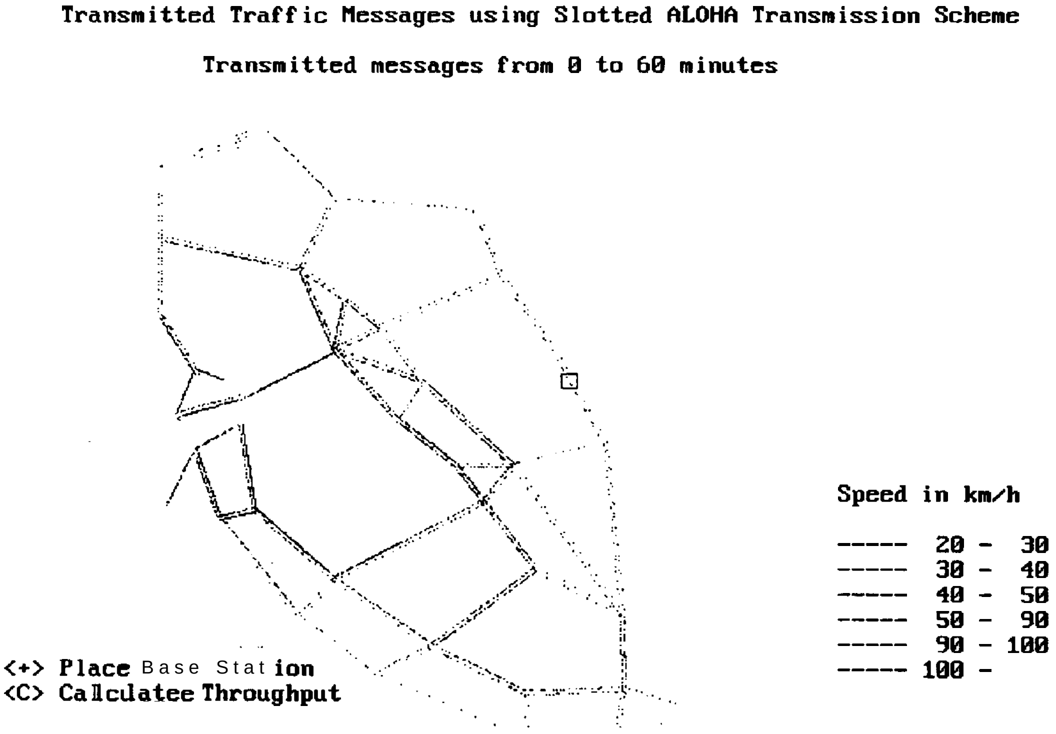


```
Transmitted Traffic Messages using Slotted ALOHA Transmission Scheme
          Transmitted messages from 0 to 10 minutes

                                        Speed in km/h

                                        -----  20 -  30
                                        -----  30 -  40
                                        -----  40 -  50
                                        -----  50 -  90
                                        -----  90 - 100
                                        ----- 100 -
```

Figure 22 Traffic messages transmitted by simulated probe vehicles



```
Transmitted Traffic Messages using Slotted ALOHA Transmission Scheme
          Transmitted messages from 0 to 60 minutes

                                        Speed in km/h

                                        -----  20 -  30
                                        -----  30 -  40
                                        -----  40 -  50
                                        -----  50 -  90
                                        -----  90 - 100
                                        ----- 100 -
<+> Place Base Station
<C> Calculatee Throughput
```

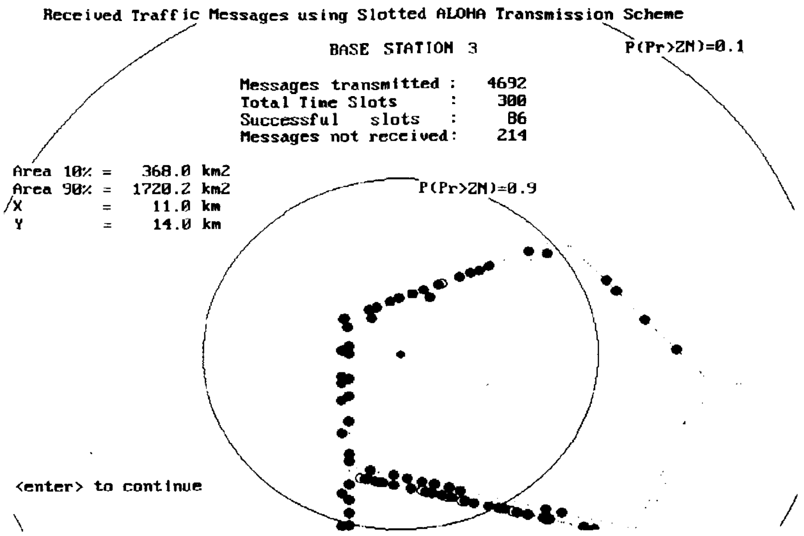
Figure 23 Traffic messages transmitted by simulated probe vehicles

As the probes are simulated sequentially, a data base of transmitted traffic messages is built, ordered to probe vehicles. This data base is then sorted on time. Plotting the entries in this time-sorted data base gives a picture of the traffic flow as it would be reported by probes. Figures 22 and 23 show two snapshots of this process. Each dot represents a transmitted traffic messages. The hue of the dots indicate the perceived speed according to the legend in the lower right comer. In the screen of figure 23 the base stations can be placed in the same way as already described for the analytical model.

Simulation of spatial throughput differs from the analysis. In the analytical approach, we focus on one particular road link. In the simulation model, on the other hand, we address particular traffic messages and calculate the probability that it will be received by any of the listening base stations. A random experiment is performed to determine whether the packet captures the receiver. The results of the throughput calculation for one base station are depicted in figure 24. Large dots represent successfully received traffic messages, smaller dots represent transmitted traffic messages that could not capture one of the base stations. Again, the hue of the dots indicates the perceived speed.

Combining the throughput per base station and accounting for site diversity gives the total amount of received traffic messages. The result for the default values, specified numbers and our particular locations of base stations is in figure 26. If all base stations are connected to a traffic management center by a wireline infrastructure, the result in figure 26 represents the traffic information as it becomes available in the Traffic Management Center (TMC). Based on this information traffic control strategies can be deployed and information can be disseminated.

The results of the simulation are subject to stochastic variations from sample path to sample path. To avoid the need of averaging over multiple runs, the analytical approach has been used for further investigations.



```
Received Traffic Messages using Slotted ALOHA Transmission Scheme
                         BASE STATION 3

              Messages transmitted :   4692
              Total Time Slots     :    300
              Successful   slots   :     86
              Messages not received:    214

Area 10% =   368.0 km2
Area 90% =  1720.2 km2
X        =    11.0 km
Y        =    14.0 km

<enter> to continue
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Figure 24 Calculation of spatial throughput for simulated probes for one base station

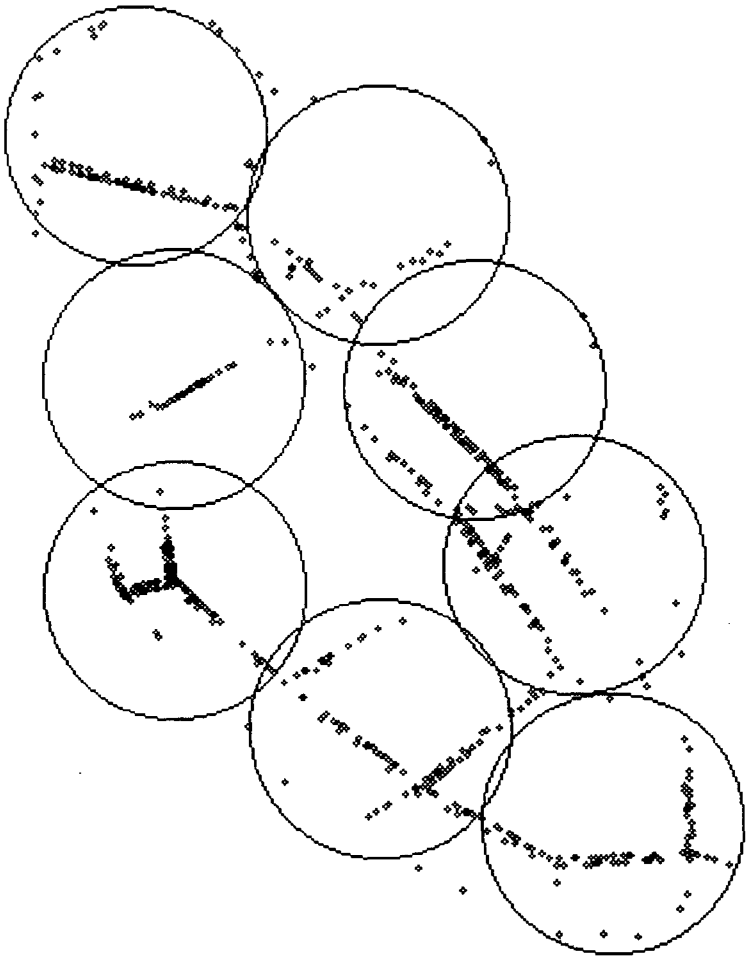

Figure 25 Total amount of traffic messages received by the base stations

5 Results

We have developed the computer tool PROMOT (PRObe vehicle concept for MOnitoring road Traffic) to assist the planning of probe vehicle radio networks. This tool allows rapid investigation of the performance of particular network solutions and cell lay-outs. This sections reviews the most significant effects of system parameters. In particular, we address the effect of propagation distance and probe vehicle penetration rate.

Initially we interpret the theoretical results in section 3.6, to predict the effect of distance and penetration rate qualitatively.

5.1 Qualitative effect of distance

The expressions for probability of capture in section 3.6 and Appendix A reveal that the number of successful messages, received from link ***a*** highly depends on the distance from this link to the base station, ***r(a).*** In case of a noise-limited, i.e., a lightly loaded, system, the probability of successful reception is of the generic form

$$P_{NA} = \exp\{ -c_1 r(a)^4 \}$$

with c_1 a constant which mainly depends on antenna heights, transmit power, carrier frequency and the power of the channel noise. Thus, beyond a certain distance, the probability of successful reception drops rapidly. The coverage circles estimated by the tool give a good indication of the performance of lightly loaded system.

In a heavy-loaded, contention-limited network, the probability of success starts to decrease at shorter range, but it decreases more slowly. In the extreme case of a perfectly uniform spatial distribution of vehicles over a large area (Linnartz 1993), it can be shown that

$$\mathrm{P}(A_a \mid r_a) \approx \exp\{ - c_2\, r(a)^2 \}$$

with c_2 a constant which mainly depends on message traffic intensities.

5.2 Qualitative effect of penetration rate

The effect of increasing penetration rate ζ is understood from our mathematical expressions: As seen from equation (9) in section 3.6, the throughput per link per base station is of the generic form

$$S(a) = c_3 \zeta / T \exp\{ -c_4\, \zeta\, r(a)^2 / T \}$$

where the constants c_3 and c_4 depend on the road network lay-out and on vehicle densities. This expression confirms that throughput initially always increases with increasing ζ but beyond a certain penetration it decreases rapidly. It has been computed (e.g., Linnartz, 1993) that with increasing penetration rates, the total number of messages accumulated over all links remains fairly constant, but the origin of the messages becomes more and more restricted to very nearby links. This has. been derived from a simplified model that unrealistically distributes probe vehicles uniformly over the earth surface, irrespective of any road infrastructure. Experiments with our road traffic model confirm that ***total*** throughput is indeed not so sensitive to the traffic load, expect for very large penetration rates ($\zeta > 10\%$). Once the network has been deployed, the operator expects the share of probe vehicles, ζ, to grow. Then the transmission parameter ***T*** can be used to optimize performance. The undesirable effect that with increasing penetration rates, fewer messages from remote links will be received can easily be avoided by appropriately reducing ***T.***

In order to investigate the above effects of distance and penetration rate quantitatively in the San Francisco freeway network, we studied base stations at three critical locations (see figure 26). Location A (figure 26, top, toll plaza of the Bay Bridge) has heavily occupied road links very nearby. Location ***B*** (figure 26, middle, San Mateo Bridge west entrance) is surrounded by several road links with high traffic intensities, plus several road links with low traffic occupancies. Location C (figure 26, bottom, Dumbarton Bridge west entrance) is located in a fairly quiet traffic environment.

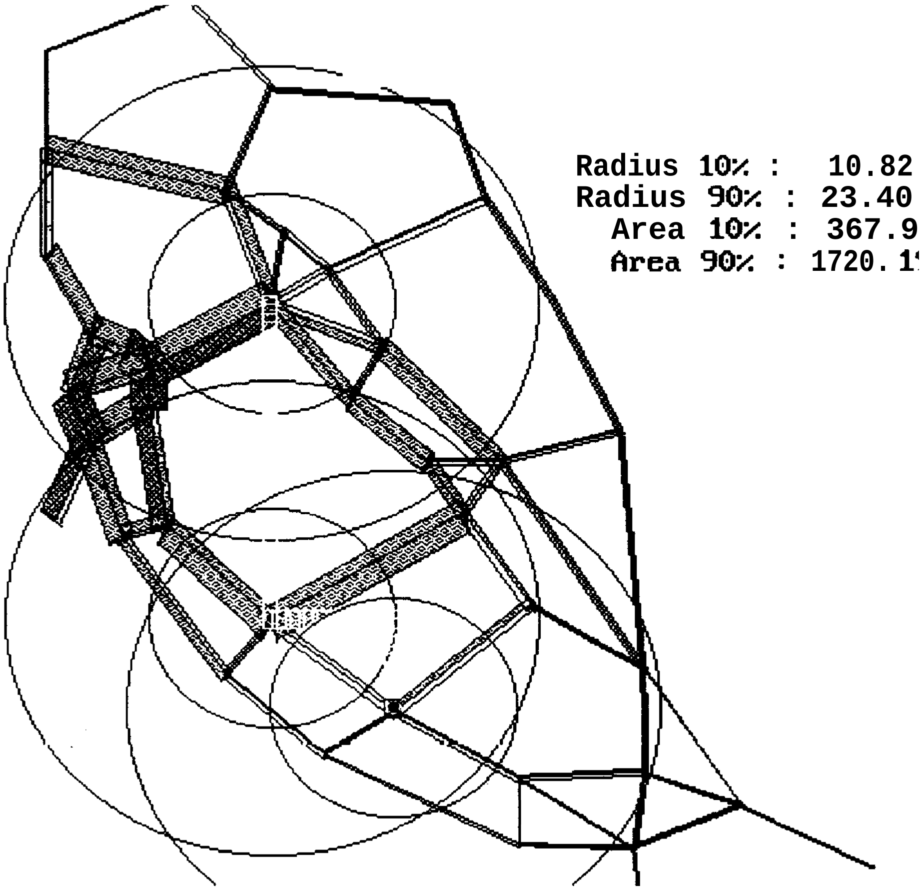

Figure 26 Three different locations of base stations (A, B & C)

5.3 Low penetration rates

Figures 27, 28 and 29 give message traffic as a function of distance $r(a)$ of road link a. ***The*** number of transmitted traffic messages per time slot from that road link, $G(a)$, is proportional to the link traffic density $D(a) = Z_a q_a$. This ‘attempted’ message traffic is denoted by bars in the graphs. The expected number of received traffic messages per time slot from that road link $S(a)$, has been computed, taking into account interference from other links. Results are presented as solid lines. In these figures, the probe vehicle penetration rate ζ is 0.1%, the number of time slots preserved for probe vehicle transmissions f_s is 18, the mean time interval between transmissions T is 60 seconds. Site diversity is not considered here.

The graphs show that beyond a certain distance, the number of messages received in the base stations from a road link substantially decreases as the distance between the base station and the road link increases. This effect occurs in all three situations. The maximum distance from where transmitted messages are still received is approximately 25 kilometers. Path loss and noise are the main mechanisms of packet loss. A design with 18 slots per second is amply sufficient to accommodate the message traffic flow. Accordingly, the probe vehicle concept with random acces radio channel proves to be indubitably appropriate. On the one hand, it allows a simple system architecture, simple in-vehicle equipment, simple management procedures in the Traffic Management Center and is well protected against possibilities for privacy intrusion. On the other hand, it enables an efficient method for collecting real-time road traffic data.

Figures 30, 31 and 32 give screen dumps of the performance estimates, for base station locations A, B and C, respectively. The 10 %-coverage circles have a radius of about 10 km, but many messages are received from outside these circles. The thickness of the road links in the figures represent the intensity of car traffic and the hatches of the links indicate the estimated number of received traffic messages from the road links according to the specified AID and (A)TM/IS requirements. Again, we point out that these requirements are preliminary and have been established without thorough research. Therefore, the hatches only give some indications whether AID, ATM/IS or (traditional) TMIS can be deployed. The exact number of probe vehicle messages (per kilometer) per link per minute required to perform reliable AID and (A)TM/IS is to be investigated further.

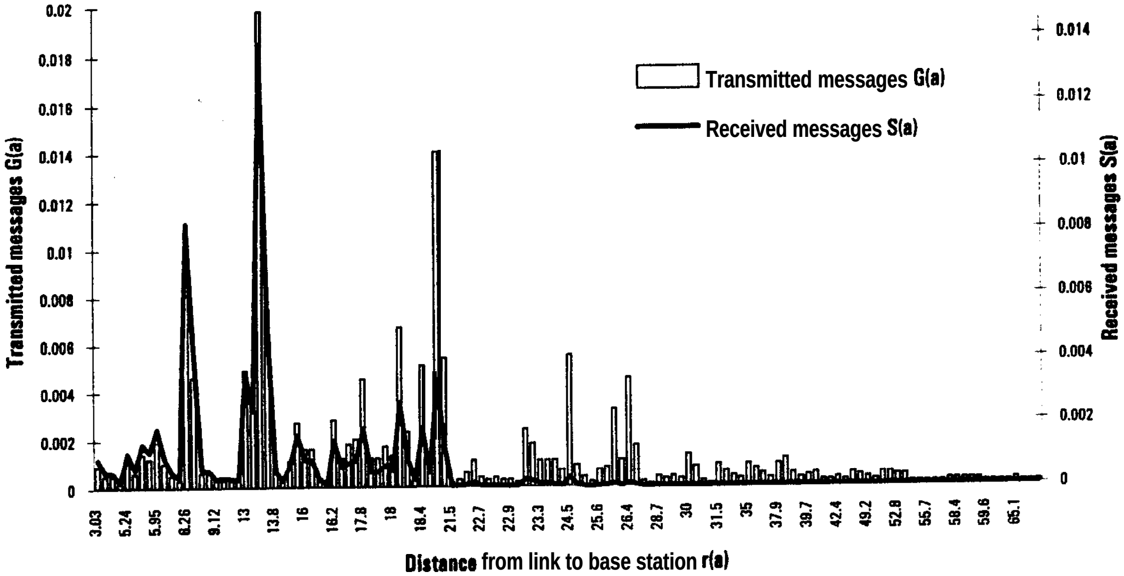

Figure 27 Throughput in base station A per road link as function of traffic density

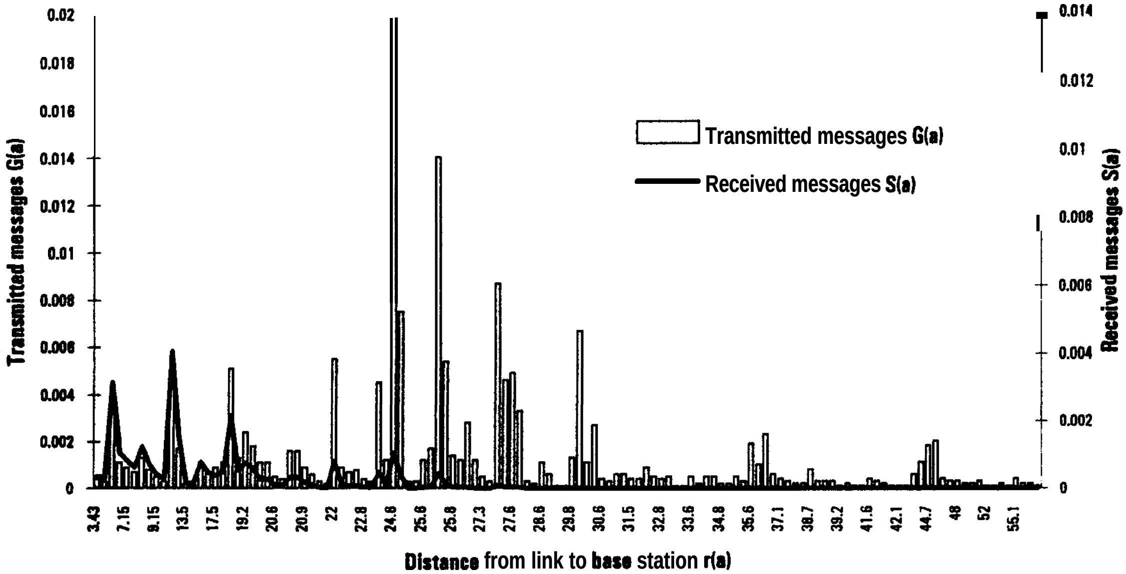

Figure 28 Throughput in base station B per road link as function of traffic density

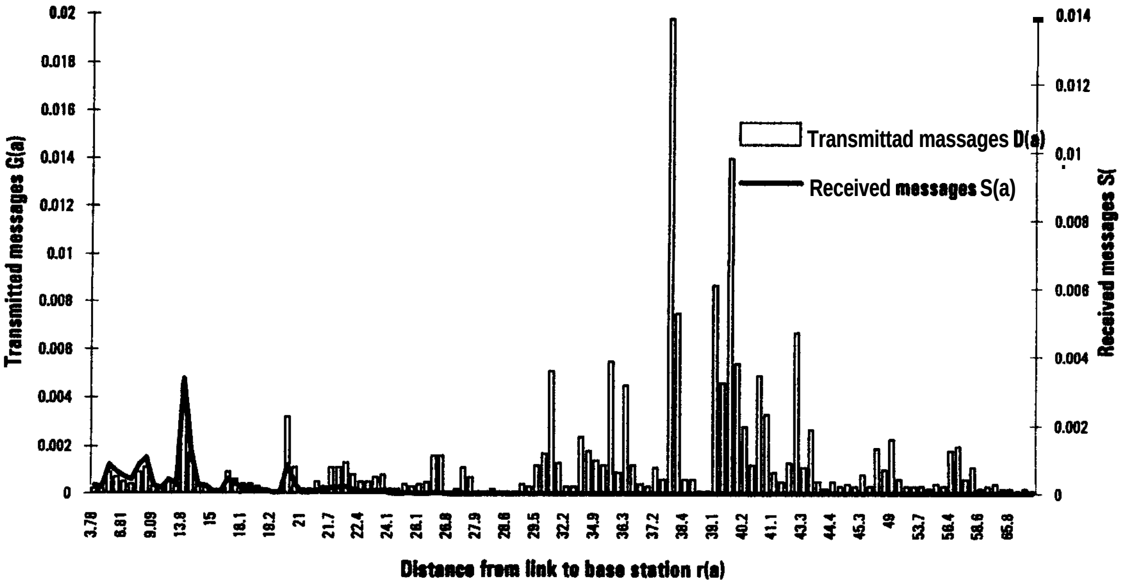

Figure 29 Throughput in base station C per road link as function of traffic density

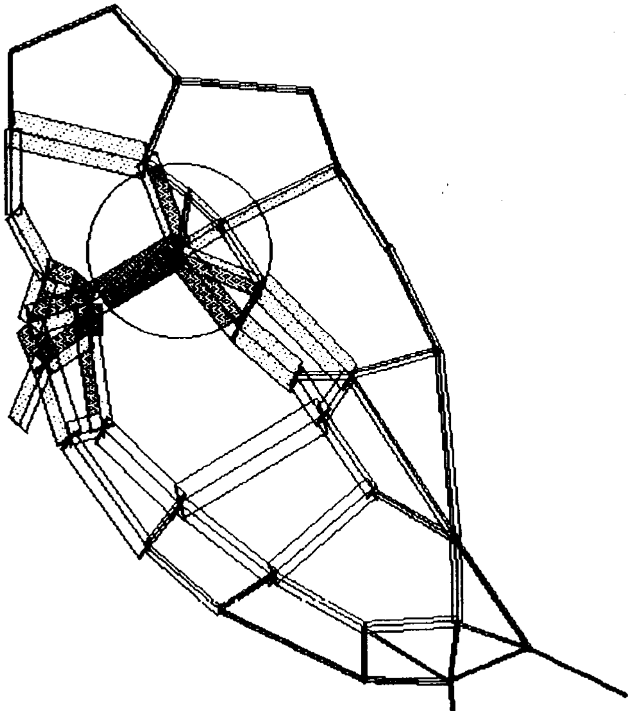

Figure 30
Throughput per road link in base station A (Toll plaza of the Bay Bridge)

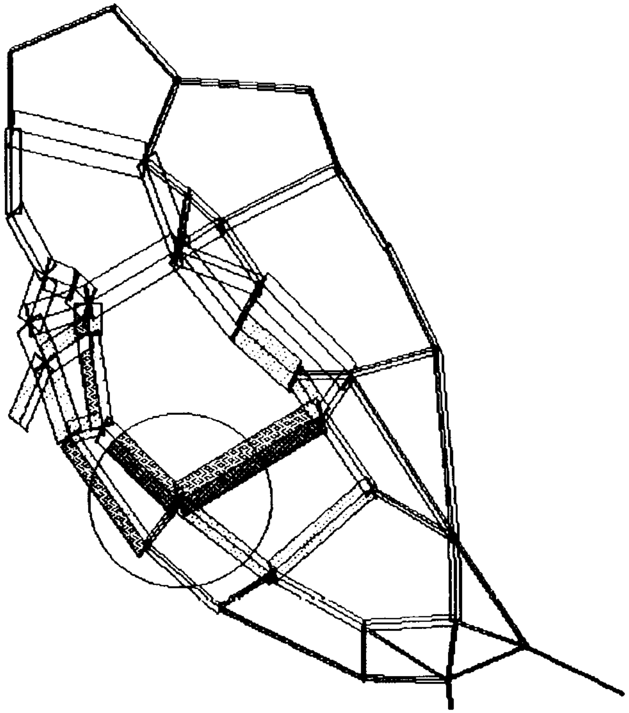

Figure 31
Throughput per road link in base station B (San Mateo Bridge west entrance)

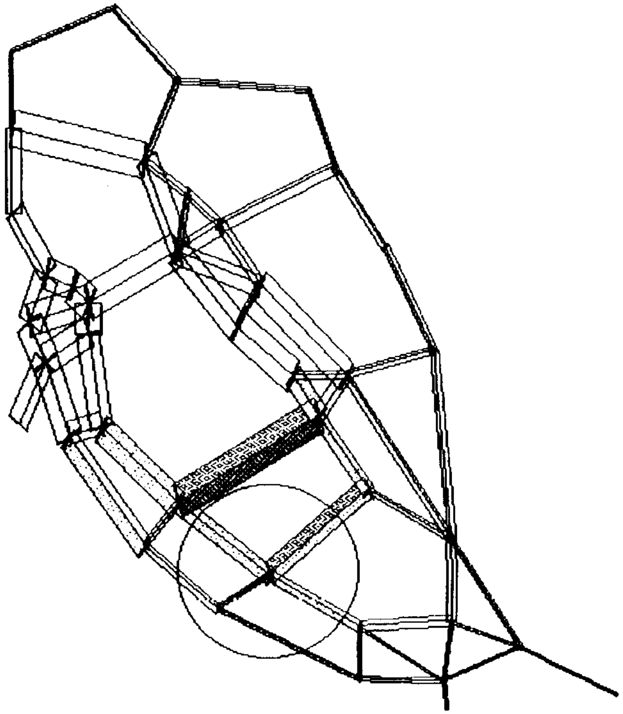

Figure 32
Throughput per road link in base station C (Dumbarton bridge west entrance)

5.4 Moderate penetration rates

With increasing probe vehicle penetration rate, message collisions and mutual interference become more important as a factor limiting network performance. As more probe vehicles transmit traffic messages, the messages from links close to the position of the base station harmfully interfere with messages transmitted from farther links. This means that an increasing probe vehicle penetration rate limits the practical cell-size from which a base station receives probe reports.

In case of a small penetration rate (e.g. 0.1% in graph 28), messages could be received over ranges of up to 25 km. The total amount of offered traffic messages is small enough, this means much smaller than the number of available time slots, the ensure that the total number of offered messages remains relatively small. Hence, the communication needs are well within the channel capacity. If the penetration rate is increased, two effects occur:
The number of attempted messages increases, which initially increases the number of successfully received messages. At the same time, the probability of a harmful collision with other (strong) messages also increases. This effect will dominate if the penetration rate is increased further.

Our investigations for $f_s = 18$ and $\boldsymbol{T} = 60$ reveal that if the penetration rate exceeds approximately 5 % ($\zeta = 0.05$), the channel capacity significantly limits the throughput of the probe messages. This study is limited to freeway traffic. Presumably, these results will differ significantly if also traffic on secondary roads is taken into account. For this, we have started investigating the performance of the probe vehicle concept in an urban area road network (Eindhoven in the Netherlands).

With growing penetration rate, initially, only throughput from remote road links is affected. Virtually no messages are received from links at more than circa 14 km. Throughput from nearby links, however, is large, particularly if they contain dense road traffic. This effect is illustrated by the next three graphs (33, 34 and 35). These graphs contain the same results as graph 28, but now with a probe vehicle penetration rate of 1% , 5 % and 10 % respectively.

At small probe vehicle penetration rates (up to 1%) the radius of the cells of the base stations could amount to circa 25 kilometers. At moderate penetration rates (1 to 5 %) the cell size of the base stations is limited to a radius of about 14 kilometers. From the road links within this cell, much more traffic messages are received successfully. In consequence, at modest probe vehicle penetration rates of circa 5 % the coverage area of the base stations is relatively small. This necessitates more base stations. The combination of more probe vehicles and more base stations is very beneficial for the throughput per road link.

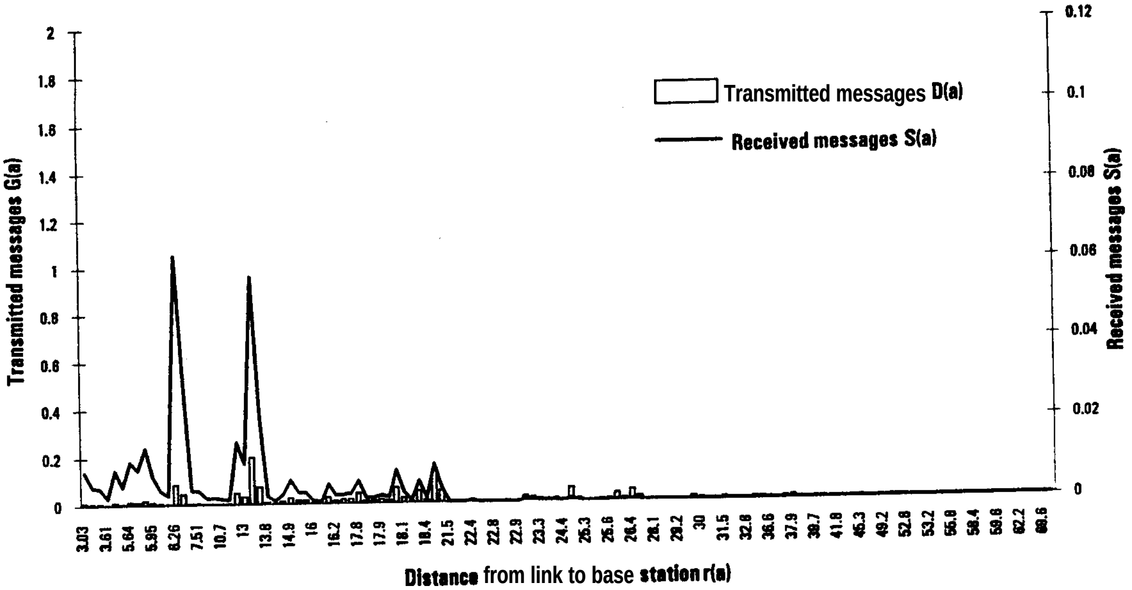

Figure 33 Throughput in base station A per road link as function of traffic density: ζ = 1%

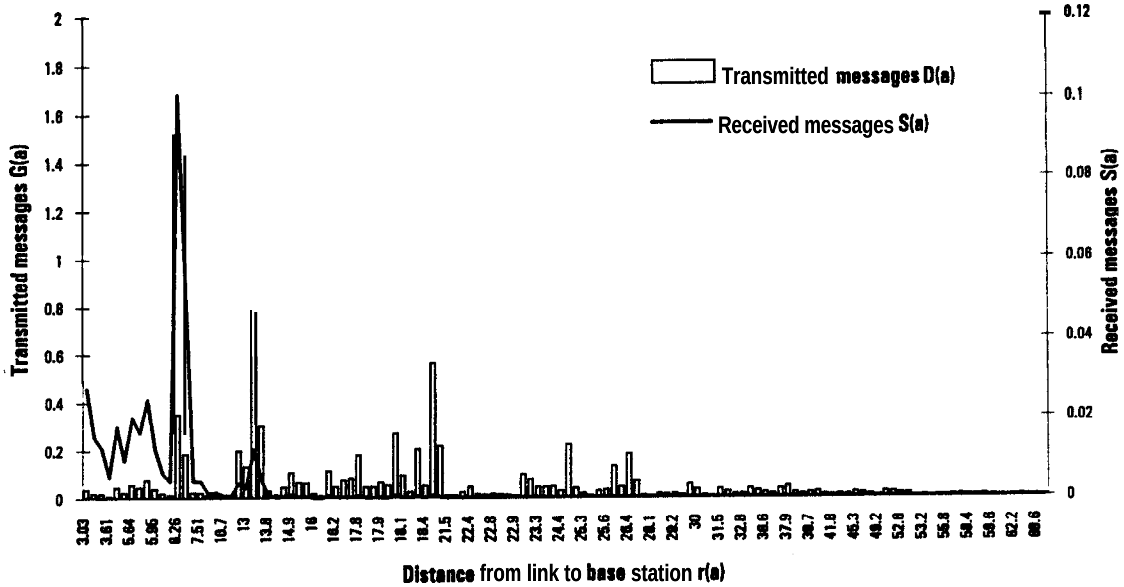

Figure 34 Throughput in base station A per road link as function of traffic density: ζ = 5%

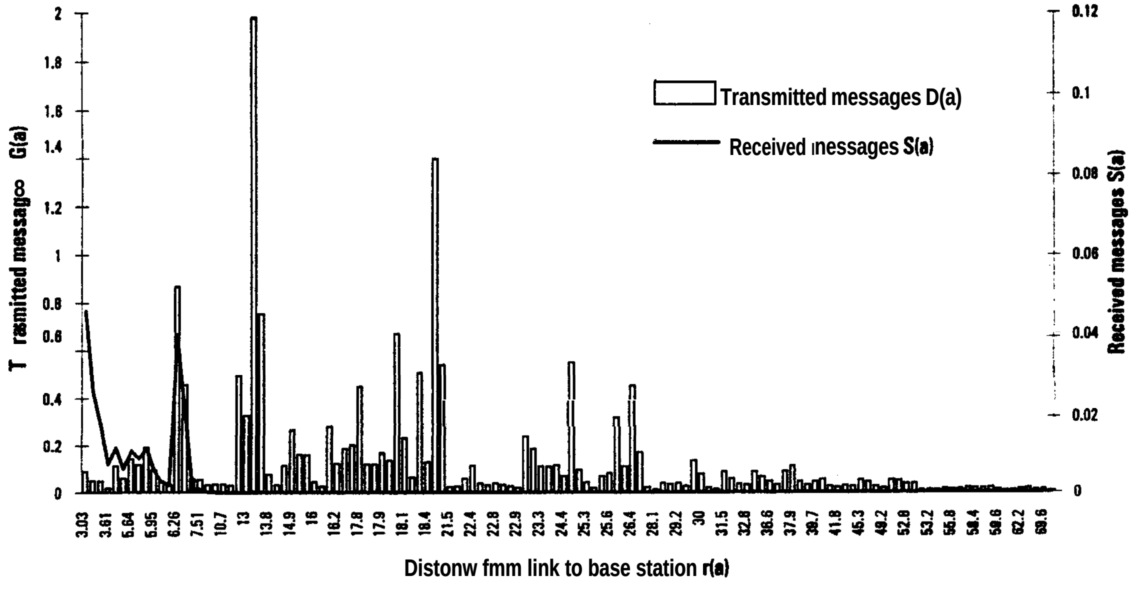

Figure 35 Throughput in base station A per road link as function of traffic density: ζ = 10%

5.5 High penetration rates

Simplified theoretical models with perfectly uniform offered traffic suggest that the total throughput accumulated over all links remains constant if the offered traffic per unit area increases (Linnartz, 1993). However, with increasing offered traffic, only messages from very close to the receiver contribute to the throughput. More realistical models, taking into account that vehicles are always at least separated some minimum distance from the receive antenna, show a vanishing throughput with increasing offered traffic. For the San Francisco Bay Area modelled in graph 39, beyond a penetration rate of 10%, the total number of traffic messages captured by base stations decreases substantially, unless the transmission interval T is increased appropriately.

Graphs 36, 37 and 38 all address the number of received traffic messages from four specific road links at certain distances (approximately 3, 6, 9 and 12 kilometers) from a base station. The base stations are located at positions A, B and C in figure 36, 37 and 38, respectively. The throughput is depicted as a function of probe vehicle penetration rate.

For all three locations we see that, the throughput of each road link increases with increasing probe vehicle penetration rate. If the base station is located in an area with heavy traffic, as is the case at location A, the throughput of the remote links (12 and 9 km respectively) already decreases at a low penetration rate (1 and 2 % resp.). At a penetration rate of about 4 % , the throughput of more nearby links (6 km) is affected also. Monitoring the road link at about 3 km continues to improve up to a relatively large penetration rate (10 %) and remains possible until about 50% of all vehicles serves as a probe and transmit once every minute.

For base stations placed at position B (graph 37) and C (graph 38), we see similar effects. Many traffic messages are transmitted from the road link 6 kilometers separated from the location B. For this reason the number of traffic messages received from this link continues to exceed the number of messages received from the closest link. For a high penetration rate of about 25 %, the total number of competing messages is too high and the performance of monitoring the remote, heavily occupied road link severely diminishes in favour of the nearest road link.

In the latter situation (base station at position C), there are relatively few messages from nearby the base station so more traffic messages from links further away are received. However, at an increasing penetration rate, traffic messages from the nearest link conflict harmfully with remote messages. These graphs show that it is difficult to make a general judgement about the effect of an increasing probe vehicle penetration rate.

At any particular distance; the number of successfully received messages decreases if the offered message traffic increases without bounds. Except in the unrealistic case that transmitting probes can be arbitrarily close to the base station, the total throughput received at a base stations eventually also approaches zero. Graph 39 shows the total throughput per base station as function of the probe vehicle penetration rate.

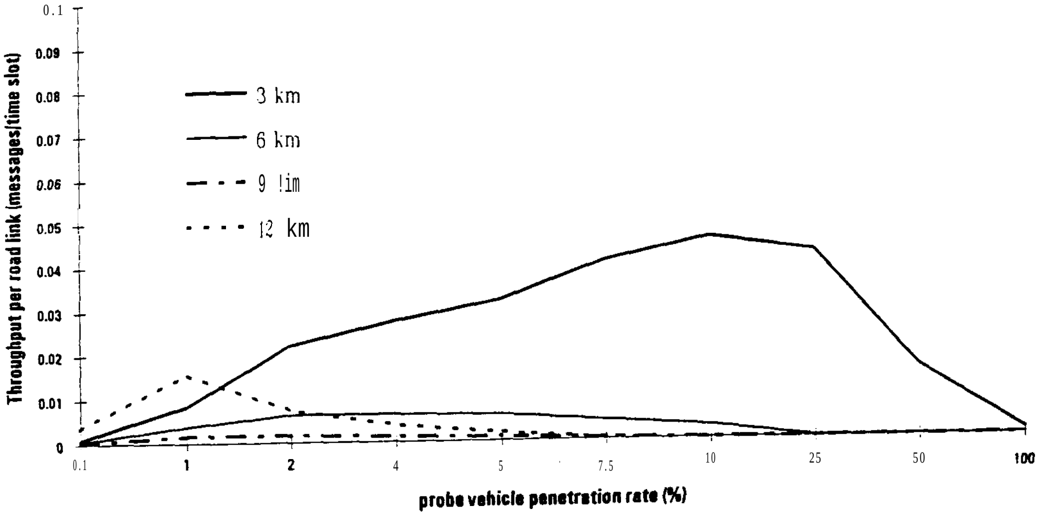

Figure 36 Throughput per road link at several distances as function of penetration; location A

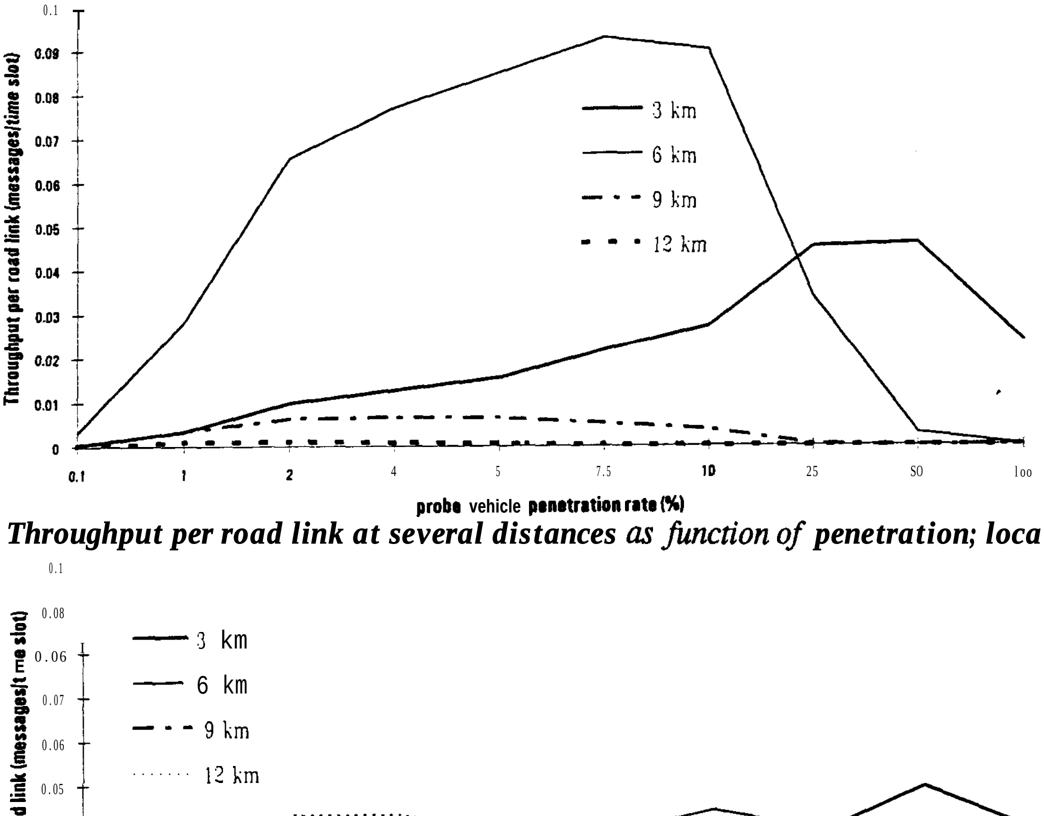

Figure 37 Throughput per road link at several distances as function of penetration; location B

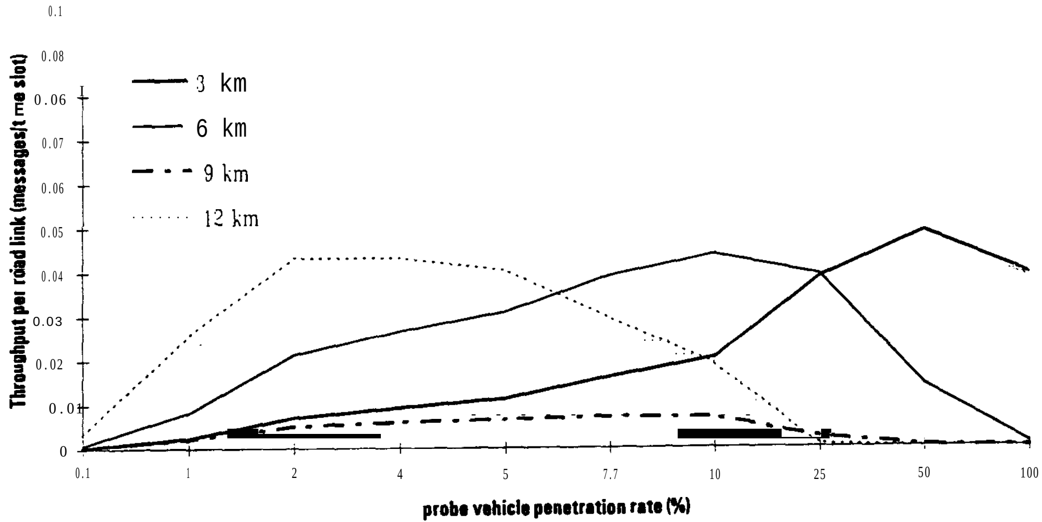

Figure 38 Throughput per road link at several distances as function of penetration; location C

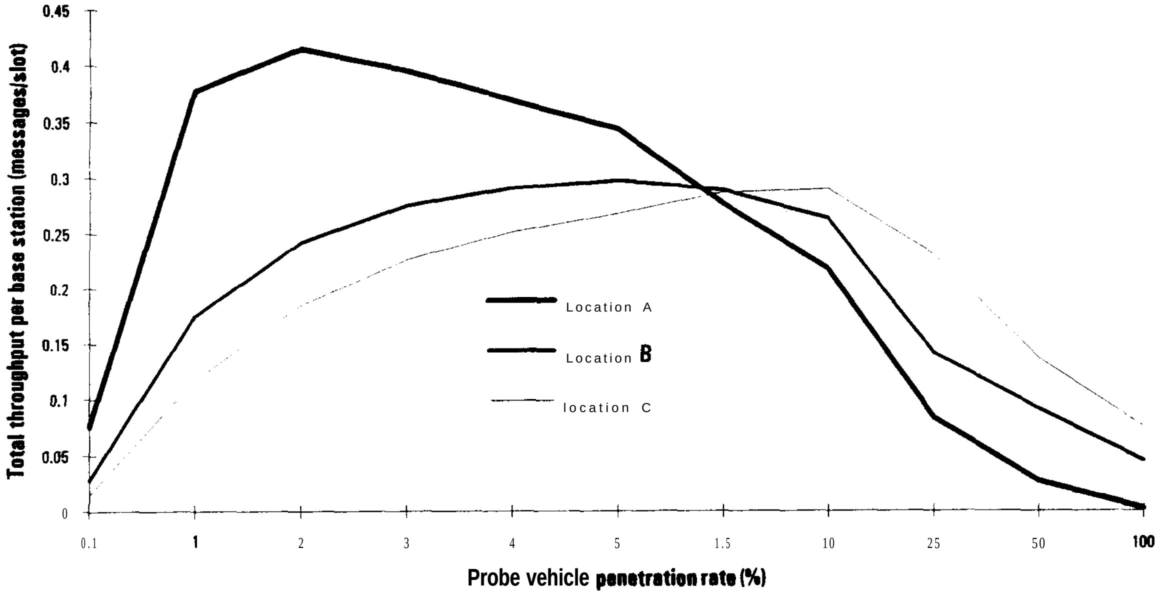

Figure 39 Spatial throughput as function of distance and traffic density (per road link)

From these results it has become clear that at high probe vehicle penetration rates (more than circa 5 %) the traffic message throughput diminishes, even from the road links nearby the base station. In this case the transmission interval ***T*** has to be adjusted to assure adequate traffic monitoring. This adjustment can be semi-dynamically or dynamically, subordinate to the actual traffic situation. In this way, a solid traffic monitoring system can be constructed with a high quality performance under all circumstances (low, moderate and high probe vehicle penetration rates) and suitable for all aspired applications (Automatic Incident Detection and (Advanced) Traffic Management / Traveler Information Systems).

6 Discussion

Properties of the probe vehicle system using random acces transmission scheme
The graphs in the previous chapter reveal that the road areas that can be monitored adequately, critically depend on the location of the receiving base stations. Moreover it depends on the spatial distribution of the offered traffic, i.e., from the lay-out of the road network, the amount of road traffic and the intertransmission time chosen by the probe vehicles. At a relatively low probe vehicle penetration grade ($\zeta < \pm 1\%$) the distance between a certain road link ***a*** and the receiving base station, ***r(a),*** is the most important factor influencing the throughput of that road link ***S(a),*** followed by the (probe) vehicle density on that road link, ***D(a).*** If the probe vehicle penetration grade becomes sufficiently large ($\zeta > \pm 1\%$), the size of coverage area of a base station diminishes and the number of participating probe vehicles on a road link within the ‘cell’ becomes less critical, particularly since the intertransmission interval can be optimized to avoid loss in throughput due to excessive message collisions. These effects are an evident consequence of the ALOHA random acces radio system.

Properties of probe vehicle systems in general
From a traffic engineering prospective, the possibly distorting effect that road density and distance to the base station have on throughput is very relevant to develop new methods for road monitoring using probe vehicles. For traffic control, continuous traffic monitoring, reliable estimation of actual and future traffic conditions and quick detection of disturbances of the traffic flow are essential. To this end, three distinct categories of traffic flow parameters can be distinguished:

1) traffic density ***k,*** expressed in ***vehicles/km,***
3) traffic ***flow*** q, expressed ***in vehicles/hour,*** and
2) speed u, expressed ***in km/hour.***

The relations between these traffic flow parameters constitute the three so-called fundamental diagrams ***(q/u, q/k*** and ***u/k) (see*** for instance (May, 1990)).

The parameters of the first two categories (density and flow) can only directly be determined from measurements of (nearly) all vehicles on a road link or segment[1]. This can be explained by optimistically assuming that the penetration grade ζ of probes is exactly known. Typically, ζ is in the order of 0.1 to 10 with low ζ prevailing during the early introduction phases. The traffic flow is monitored using small and discrete time periods of for instance 1 or 5 minutes. Due to fluctuations in the composition of the traffic flow the actual number of probes present on

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[1] The ALOHA system appears fundamentally unsuitable for monitoring category 1 parameters, because of the near-far effects in the spatial throughput. There is however a clear case where a random access radio link can estimate density or flow, if the receiver is located along a freeway, and considers only messages generated by cars on that freeway. If the penetration rate of radio transmitter is large and known, for instance if the radio system is also used for electronic toll collection, then it can accurately measure the number of cars passing the receiver.

a road link in a certain time period will vary to such a extend that no reliable statistical conclusions on traffic density can be drawn from received probe vehicle messages. Moreover, the capture process of the proposed (slotted) ALOHA transmission scheme introduces randomness in the received throughput as not all transmitted traffic messages will be received by a base station. Furthermore, the offered traffic $G(a)$ and traffic density k_a are not a (uniquely defined) function of the throughput $S(a)$. Even if one could know the statistics of the interfering traffic from other road links exactly, two solutions for $q_{a0}Z_{a0}$ exists in equation (10).

For obtaining the parameters of the third category (speed or travel time) the probe vehicle system concept in general (and the proposed system using ALOHA transmission scheme in particular) is preeminently suitable. Traffic data collected by traditional (fixed) detectors concerns data of a cross-section of a road link only. The second category parameters however regard data of a longitudinal section of a road link, while deriving longitudinal section data from cross-section data can introduce significant deviations and is unreliable. The results of this study showed that travel times can reliably be obtained through probe vehicles, even if their penetration rate is low.

The properties of the probe monitoring technique system are thus complementary to those of loop detectors, which are useful for determining flow and density (category 1 and 2), but less suitable for determining travel times or longitudinal speed (category 3). We surmise that the combination of probe vehicles with loop detector allows the development of novel traffic monitoring techniques that substantially outperform existing methods. However, the fundamental properties and behaviour of these new methods are not yet know and fundamental studies appear necessary. At the moment, even for systems using only probes, thus without loops, it is unknown how many vehicle samples are required to reliably estimate the probability density function of the vehicle travel time (see also Boyce, Hicks and Sen, 1991) or to perform Automatic Incident Detection (AID). For AID simple algorithms exist based on induction loop data, but not based on probe measurements. Such algorithms are yet to be researched for probe data or combined probe vehicle/induction loop data.

Control of the transmission interval T

The usefulness of a traffic monitoring system using probe vehicles is among others related to the amount of received messages from the road links. This depends on the number of offered, i.e., transmitted massages per unit of time, $\zeta q_a Z_a / f_s T$. This is determined by the number of vehicles per road link, the penetration rate of probe vehicles, and their transmission protocol. As the offered traffic increases, the distance between link and base station becomes increasingly important. Mutual interference of messages can be controlled effectively by appropriately adjusting the transmission interval T. This study showed that it is presumably necessary to dynamically adjust T, according to the actual radio traffic density, optimizing the throughput. In a more advanced system,. one could make the transmission scheme T depending on the actual road traffic conditions, examples are:

more reports from links where an incident is suspected to have happened ,
more reports from links where few (probe) vehicles are present,
more reports from secondary roads,
more reports from links far away from any receiving base station, or
transmission of reports only if travel time differs from daily average.

Penetration rate required for reliable ATMIS

In many expressions, the parameter $\zeta q_a Z_a / f_s T$ appears. This misleadingly suggests that the ATMIS performance only depends on the ratio ζ / T. Yet, the quality and the reliability of the information about the actual traffic conditions that can be deduced from the data in the probe vehicle samples is the important criteria. When the penetration rate is very low, this can of course not be compensated by a very short intertransmission interval. From a traffic engineering prospective it is not very useful to have the same, few vehicles transmit unlimitedly frequent. In these cases the TMC may often receive messages from the same probe, which may bias the sample set to the behaviour of one particular driver. More insight is needed into the effect of correlated samples per link, taken from a limited set of probes only.

Analyses (e.g. graphs 34, 35 and 36) indicate that a reasonable value of ζ / T appears to be in the range of 1 to 4, greatly depending on the transmission scheme, e.g. the values of f_s = 18, the throughput requirements for ATMIS services, and (as shown in graphs 37, 38 and 39) on the traffic situation in the vicinity of a base station. Without having specified proper ATMIS requirements it is difficult to make a general judgement about the minimum or optimum probe vehicle penetration rate. Assuming

our specified default throughput thresholds for AID and (A)TMIS:
    AID: 3 messages per link per minute,
    ATMIS: 5 messages per link per 5 minutes and
    traditional TMIS: 1 message per link per 5 minutes
a ζ / T ratio of ($\zeta / T = 4$)
an intertransmission time of at least T = 1 minute
18 time slots per second preserved for uplink probe vehicle transmissions (f_s = 18),

a probe penetration rate of 4 % (ζ = 4 %) is required for sufficiently reliably monitoring the freeway links by means of the proposed probe vehicle system. Cattling (1994) expects that a penetration rate of dynamic route guidance systems will be 5% by 2000. Until such penetration rate is reached dynamic route guidance may be offered and (A)TMIS may be deployed, but AID may not be feasible though probe vehicle monitoring.

We would like to emphasize that for conclusive inferences with respect to the probe vehicle penetration rate required for reliable ATMIS, more fundamental knowledge is needed about:

- the information requirements of the various ATMIS applications, in particular:
    - the kind of information, and
    - the accuracy and reliability of the information,
- procedures and algorithms for deducing the above mentioned information from collected road traffic data,
- the requirements of the collected elementary traffic data, in particular:
    - the number of (probe vehicle) samples needed to reach the required level of accuracy and reliability of the above mentioned information.

We used the above parameters for a tentative design of lay-out of base stations for monitoring the San Francisco Bay Area during peak hours. Figure 40 (simulation) and 41 (analysis) show that 10 base stations offer highly sufficient throughput from all road segments. In this situation high quality AID can be performed on all major road links and reliable ATMIS is possible on the complete San Francisco Bay Area freeway network.

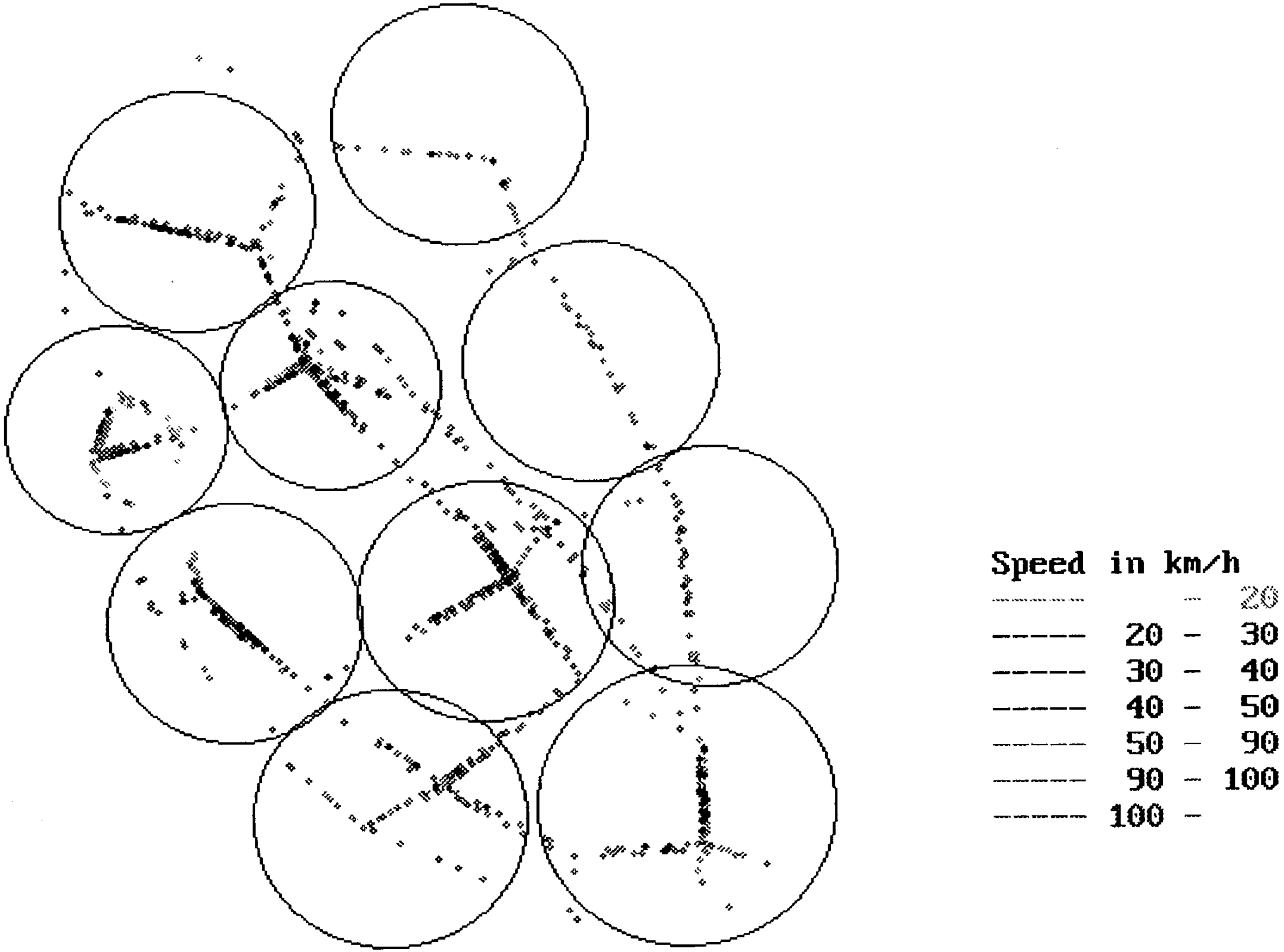

Figure 40 System configuration for monitoring the complete freeway network of the San Francisco Bay Area during peak hours using probe vehicles and random acces radio channel (simulation tool)

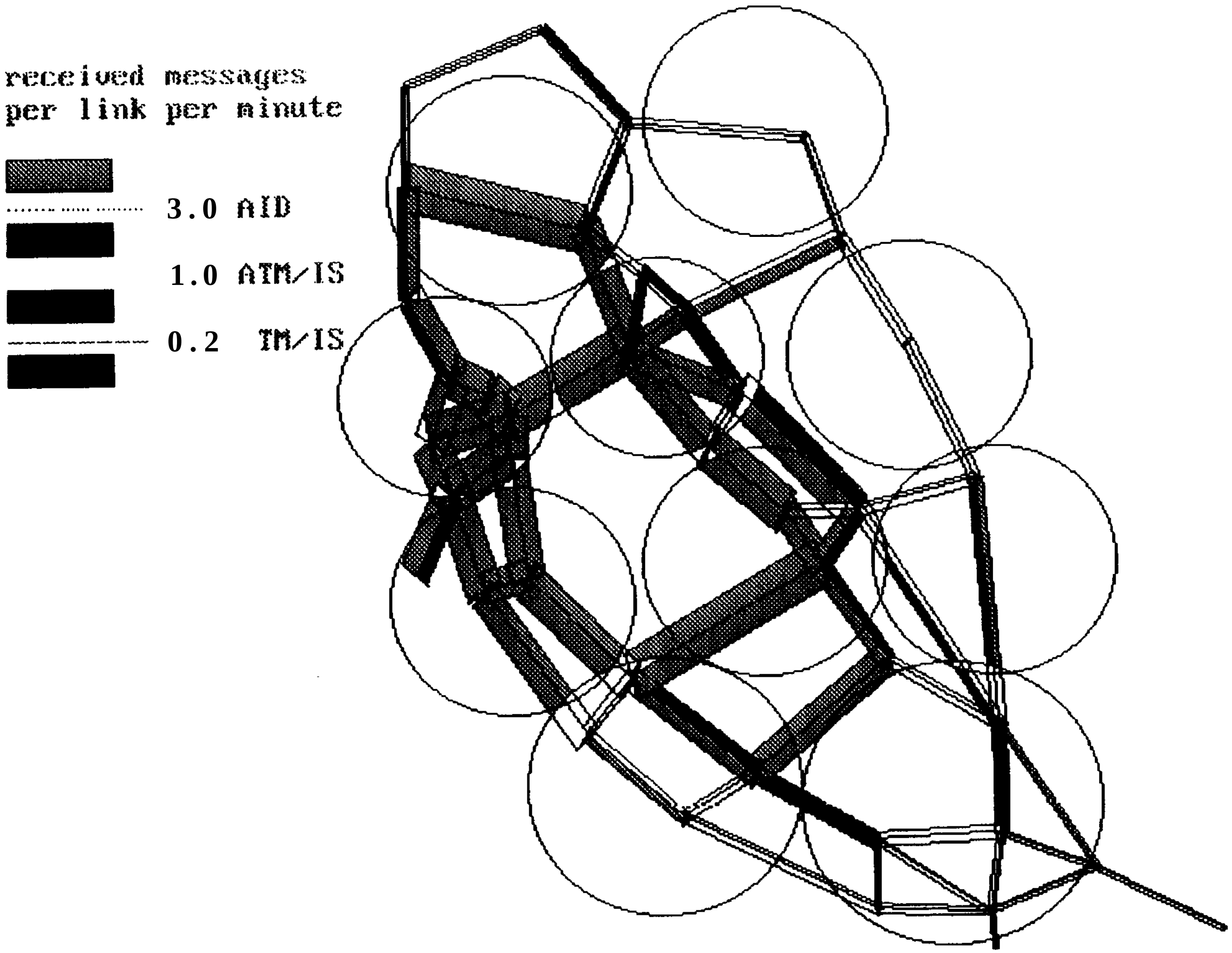

Figure 41 System configuration for monitoring the complete freeway network of the San Franciso Bay Area during peak hours by probe vehicles (analytical tool)

7 Conclusions

A very suitable means of real-time monitoring the traffic situation on a road network is to collect real-time travel times from roving probe vehicles. We addressed a random-access (slotted ALOHA) transmission scheme and found it a (spectrum) efficient, inexpensive and flexible method for transferring traffic reports from probe vehicles to listening base stations. Such a probe vehicle system can be part of a larger system, such as a dynamic route guidance system. It provides adequate real-time road traffic data, which can be used by Advanced Traffic Management Systems for real-time traffic control and by Advanced Traveler Information Systems for supplying travel advisories.

To study the performance of the proposed probe vehicle system, we considered a realistic road traffic situation, encountered in the San Francisco Bay Area during peak hour. A road traffic flow calculation has been performed. This comprehended a simultaneous land-use and transportation model to estimate origin and destination (O-D) data and a traffic assignment model to estimate traffic flows and travel times over road links. We evaluated the relationship between transmitted and received traffic messages generated by probe vehicles participating in the road traffic. In particular, we estimated the number of successfully received messages per unit of time per link, as it depends on system parameters. In particular, the probe vehicle penetration rate, the intertransmission time, the distance to the nearest base station and the number of available time slots per second appeared relevant. Although the system receives disproportionally more messages from certain links than from others, it appeared feasible to deploy a radio system collecting travel times from probe vehicles. We estimated that at a probe vehicle penetration rate of 4 % , an intertransmission interval between transmission of 1 minute, 18 slots per second and about 10 base stations are required to adequately monitor each road link of the freeway network in the San Francisco Bay Area.

The proposed system concept can efficiently gather road link travel times. Road link densities and traffic flows may not be accurately obtained from the probe system, but methods are being developed to deduce these data and other techniques exist for directly collecting these data.

With an increasing penetration rate, or at very high road traffic densities, the intertransmission time needs to be modified to avoid excessive transmission conflicts limiting the throughput. In this way, a reliable and robust traffic monitoring system can be constructed with a high quality of performance under all circumstances (low, moderate and high probe vehicle penetration rates) that is suitable for all aspired applications (Automatic Incident Detection and (Advanced) Traffic Management / Traveler Information Systems).

Recommendations for further study

A crucial issue in any probe vehicle system is the required number of probe samples per unit of time, needed to perform various ATMIS services. This requires specification of the service, e.g. AID or ATMIS, and the algorithms and criteria to be used for these services. The number of successfully received messages is an important performance criterion. However, it is not simple to directly relate the performance of an ATMIS service, such as automatic incident detection (AID), to the throughput of probe messages per link. As yet, the processing of collected probe vehicle data into travel advisories and traffic control measures has not been addressed here. However, our continued investigations include methods for combining probe vehicle data and induction loop data. This issue will be addressed in a follow-up of this PATH project.

Moreover, further specification of the message data format is needed. For instance, one needs to specify whether link travel times or speeds are reported, and how these can be efficiently encoded. A related problem is the specification of appropriate transmission intervals, which may depend on the travel experiences by the probes.

The probe vehicle concept appears to be very suitable to collect real-time traffic data from secondary roads and roads in urban or metropolitan areas. The performance of this type of road networks was tentatively addressed in a previous PATH project, but a further study, including a realistic road traffic model, is recommended.

We further recommend a study of the transmission performance of other communication services, such as datacasting or interactive (two-way) communication, using the same model for vehicle densities. A further comparison with polling may be of interest if the performance requirements for the radio system include guarantee reception of messages for from particular vehicles. In particular, this may be relevant if the concept is applied to fleet management.

Methods for investigating other (directional) antenna patterns have been developed theoretically, but these have not yet been implemented.

The resolution of the ‘analytical’ computer tool may need to be refined. At this moment, it is assumed that propagation conditions and traffic conditions are approximately constant over one entire road link, i.e., we have not split this into separate road segments.

8 References

Abramson N. (1977) ***The Throughput of Packet Broadcasting Channels,*** IEEE Trans. Comm., Vol. COM-25, No. 1.

Boyce D.E., Hicks J. and Sen A (1991) ***In-vehicle navigation requirements for monitoring link travel times in a dynamic route guidance system,*** presented at Transportation Research Board Annual Meeting, Washington.

Catling I. (Edt.) (1994) ***Advanced technology for road transport: IVHS and ATT,*** Artech House, Boston.

Catling I. and Op de Beek F. (1991) ***Socrates: A Cellular Radio System for Traffic Efficiency and Safety*** (in French), Navigation Vol. 39, No. 153, pp 22-23., January.

Egli J.J. (1957), ***Radio propagation above 40 MC/s over irregular terrain, Proceedings*** IRE, pp. 1383-1391, October.

EURO-SCOUT (1991) ***Kooperation statt Konfrontation: dynamisches verkehrsmanagement mit EURO-SCOUT,*** Siemens AG, Muenchen, Germany.

Hamerslag R. ***(1994) Manual of the Teacher Friendly Transportation Program.***

Hamerslag R., van Berkum E.C and Replogle M.A. (1994) ***A dynamic model with elastic constraints to predict the influence of railways, roads and congestion on land use development in metropolitan areas,*** paper presented at TRB meeting, Washington.

IVHS (1992), ***An overview of the IVHS program through FY*** 1992, Washington, USA.

Jakes W.C. (1978), ***Microwave Mobile Communications,*** John Wiley and sons, New York, USA.

Levy C.J. (1992) New ***$100 Million Sensor System to Monitor New York Traffic Congestion,*** New York Times, August 29.

Linnartz J.P.M.G. (1992) ***Slotted ALOHA land-mobile radio networks with site diversity,*** IEE Proceedings I, Vol. 139, No. 1, February, pp. 58-70.

Linnartz J.P.M.G (1993) ***Narrowband landmobile radio networks,*** Artech House, Boston, USA.

Linnartz J. P.M. ***G*** (1994) ***Single Channel IVHS Network Architecture,*** report prepared for PATH.

Linnartz J.P.M.G. and Westerman M. (1994A) ***Monitoring a metropolitan freeway system using probe vehicles and random acces radio channel,*** Proc. of the IEEE Vehicular Technology Conference, Stockholm, June, pp. 410-414.

Linnartz J.P.M.G. and Westerman M. (1994B) ***Performance Analysis of Road Traffic Data Collection System,*** IEICE Transactions on Communications, Vol.E77-B, No. 7, July, pp.934-938.

LISB (1991) ***Schlussbericht Leit- und Informationssystem Berlin,*** July.

Manheim, M.L. (1979), ***Foundamentals of Transportation System Analysis,*** MIT Press, Cambridge, MA.

May A.D. (1990) Traffic Flow Fundamentals.

Metropolitan Transportation Commission (1993) Planning and Modeling Division, Oakland.

OECD (1992) ***Intelligent vehicle highway systems:review of field trials,*** Road Transport Research.

Ortúzar J. de and Willumsen L.G (1990) ***Modelling Transport,*** John Wiley and Sons, England.

Ran B. (1993) ***Some experiences of probe data analysis in the ADVANCE project,*** ADVANCE working paper, June.

Walker J. (1990) (Editor) ***Mobile Information Systems,*** Artech House, Boston, MA.

Walrand J. (1991) ***Communication networks,*** Aksen Associates, Boston, MA.

Westerman M. and Hamerslag R. (1993) ***Collecting the dynamics in metropolitan freeway systems: a simulation study,*** Proc. of 26th ISATA conference, Aachen, Germany, pp. 807-814.

Westerman M. (1994A) ***Estimation of travel times for ATMS and ATIS,*** Proc. of the 26th UTSG Conference, Leeds.

Westerman M. (1994B) ***Aspects of Mobile Communication in Dynamic Road Traffic Management,*** Proc. of the Wireless Computer Networks conference, IEEE/ICCC, The Hague, The Netherlands, pp. 1232-1236.

Westerman M., Linnartz J.P.M.G. and Hamerslag R. (1994) ***An advanced traffic monitoring system for IVHS using probe vehicles,*** Proc. of the International Conference on Advanced Technologies in Transportation and Traffic Management, Singapore, pp. 227-***234.***

Appendices

- A Radio Network Analysis
- B Specified Public Transport Network
- C Estimated Trip Ends
- D Estimated Origin-Destination Matrix
- E Specified Road Network and Estimated Road Link Flows and Road Link Travel Times

Appendix A contains a detailed analysis of the probe vehicle random acces scheme. The other appendixes contain tables used in our investigations. They are not reproduced in print here, but they are available on floppy disk.

Appendix A Radio Network Analysis

A key component of the probe vehicle system is the wireless data link from the probe vehicles to the base stations. This analysis is not neccesary for communication of the main results for many readers of this report, it is enclosed in this appendix.

1 Radio Coverage and Effect of Collisions

1.1 Channel and Capture Model

We address a radio channel with Rayleigh fading, caused by multipath reception (Jakes, 1974), and path loss according to Egli's semi-empirical model for UHF groudwave (Egli, 1957). We consider one particular 'test' signal, denoted by index 0, attempting to reach one of the base stations, denoted as $A, B, \ldots$ We assume that a message is received successfully if and only if the signal-to-joint-interference (C/I)-ratio of this signal at receiver A is above the receiver threshold z. This event is denoted as A,. For narrowband transmission, with incoherent Differential Quadrature Phase Modulation (DQPSK), z is typically in the range 4 . . 10 (6 . . 10 dB). Because of fading and path loss, the received powers are random variables. Assuming constant received power at least during a packet transmission time, the probability of successful reception is (Linnartz, 1993)

$$\Pr\left(p_{A,0} > z p_{A,t}\right) = \int_{0-}^{\infty} f_{p_{A,t}}(x) \int_{zx}^{\infty} f_{p_{A,0}}(y)\,dy\,dx \tag{1}$$

where $p_{A,t}$ is the joint interference-plus-noise power at receiver A while $p_{A,0}$ is the instantaneous power of the wanted signal at A and f_p denotes a probabilty density function. In a Rayleigh-fading channel, the instantaneous power is exponentially distributed around the local-mean power (Jakes, 1974) (Linnartz, 1993). The local-mean power will be expressed later in terms of the propagation distances, antenna heights, etc.

1.2 Product-Form Expression for Capture Probability

Assuming the local-mean power $\bar{p}_{A,0}$ to be known in (1), one can write

$$P\left(p_{A,0} > z p_{A,t} \middle| \bar{p}_{A,0}\right) = \int e^{-\frac{z p_{A,t}}{\bar{p}_{A,0}}} dF_{p_{A,t}}(x) \triangleq \chi\left\{p_{A,t}, \frac{z}{\bar{p}_{A,0}}\right\}. \tag{2}$$

where $\chi\{f,s\}$ = E[exp{-sp,}] denotes the charactereristic function (cf) of the joint interference power p_t the point s. For incoherent cumulation of N statistically independent signals, the pdf of the joint interference power is the N-fold convolution of the pdf of the individual powers. Laplace Transformation then results in the multiplication of N factors, each containing a characteristic function of the received power from an individual component. So,

$$P\left(p_{A,0} > z p_{A,t} \middle| \bar{p}_{A,0}\right) = \prod_{i=1}^{N} \chi\left\{p_{A,i}, \frac{z}{\bar{p}_{A,0}}\right\}. \qquad (3)$$

The total number of probe vehicles in the system is denoted as N, with index **i** denoting one particular probe, randomly transmitting with probability $P(i_{ON})$ where i_{ON} denotes the event that transmitter i is switched on. Since $p_{A,i} = 0$ if i is OFF, the cf becomes

$$\chi\{p_{A,i}, s\} = 1 - P(i_{ON}) + E[e^{-sp_{A,i}} | i_{ON}] \qquad (4)$$

We denote the conditional probability of unsuccessful reception A, given that (only) interfering terminal i is active as $W_{A,i}$ $(0 \le W \le 1)$, called the 'vulnerability weight' factor. Thus, $W_{A,i} = 1 - E[\exp\{-sp_{A,i}\} | i_{ON}]$. We model the receiver noise floor as an additional interfering signal with constant, i.e., non-fading power For a finite population of N terminals, the probability that a 'test' packet captures receiver A, given all locations of terminals $(i = 0, 1, 2, \ldots, N)$ becomes

$$P\left(A_0 \,|\, \{\text{all } r, \phi\}\right) = P_{NA} \prod_{i=1}^{N} \left[1 - W_{A,i}\, P(i_{ON})\right], \qquad (5)$$

where P_{NA} denotes the probability that the test signal (at distance r_0) is received successfully at A in an interference-free but noise-limited channel. Thus P_{NA} describes the 'coverage' of probe vehicle signals.

It has been shown analytically (Linnartz, 1993) that for a Rayleigh fading channel without shadowing, thus with known local-mean powers, the weight factor becomes

$$W_{A,i} \triangleq P\left(p_{A,0} > z p_{A,i} \,\middle|\, \bar{p}_{A,0}, \bar{p}_{A,i}\right) = \frac{z\bar{p}_{A,i}}{z\bar{p}_{A,i} + \bar{p}_{A,0}} \qquad (6)$$

The local-mean power $\bar{p}_{A,i}$ of signal i at receiver A is taken according to Egli's model

$$\bar{p}_{A,i} = G_A(\phi_i)\, P_i\, h_i^2 h_A^2\, r_i^{-4} \left(\frac{40\ \text{MHz}}{f_c}\right)^2 \qquad (7)$$

where $G_A(\phi)$ is the antenna gain pattern of receiver A in the direction ϕ of the probe, P_i is the (ERP) transmit power by probe vehicle i, h_i is the antenna height at the probe, h_A is the base station antenna height, r_i is the propagation distance and f_c is the carrier frequency. We have limited our investigations to omni-directional antennas with $G_A(\phi) = 1$ for all ϕ. We assume that the vehicle antenna heights and effectively radiated powers are equal for all probes.

1.3 Signal Coverage

Signals experience a noise floor with spectral power density $F\,k\,T_0$, where F is the noise factor (in absolute units; not in dB) accounting for additional man-made noise, above the thermal background noise, k is Boltzmann's constant and T_0 is the noise temperature (290 K). Requiring that the energy per bit is a factor z above the noise floor gives, in an interference-free situation,

$$P_{NA} = \mathrm{P}\left(P_{A,0} > zFkT_0 r_b\right) = \exp\left\{-\frac{zF\,kT_0\,r_b}{\bar{p}_{A,0}}\right\} \tag{8}$$

where r_b is the channel bit rate.

2 Throughput of ALOHA scheme

We average the capture probability over all possible locations of the n active interferers. The n-dimensional integral over the product can be written as the product of integrals since each (weight-) factor contains the local-mean power of only a single interfering signal. Moreover, for i.i.d locations of n interferers, the probability of the test packet capturing receiver A is

$$\begin{aligned}\mathrm{P}\left(A_0 \mid n, r_0, \phi_0\right) &= P_{NA} \int\!\!\int \cdots \int \left[\prod_{i=1}^{n} 1 - W_{A,i}\right] dF_{r_1,\phi_1} dF_{r_2,\phi_2} \cdots dF_{r_n,\phi_n} \\ &= P_{NA} \left[1 - \int W_{A,1}\, dF_{r_1,\phi_1}\right]^n\end{aligned} \tag{9}$$

where we used $\mathrm{P}(i_{\mathrm{ON}}) = 1$ for interferers known to be active.

In order to study the Poisson field of interferers, we that the limit for the number of terminals N → ∞ under the condition that the total offered traffic $N\,\mathrm{P}(i_{\mathrm{ON}}) = G_t = \Sigma\, G(a)$ is a constant determined by the total number of probes in the road network and their transmission rate. For the interfering message traffic being a spatial Poisson process, the capture probability becomes a sum of exponential functions, viz.,

$$\mathrm{P}(A_0 \mid r_0, \phi_0) = \sum_{n=0}^{\infty} \frac{G_t^{\,n}}{n!} e^{-G_t}\, \mathrm{P}\left(A_0 \mid n, r_0, \phi_0\right) \tag{10}$$

For an (practically) infinite population of probe vehicle terminals, data packets are transmitted with a spatial distribution G(a) where a denotes the freeway segment at a distance r_a from the base station. Thus

$$P(A_0 \mid r_0,\phi_0) = P_{NA} \exp\left\{-\sum_a W_{A,a} G(a)\right\}$$
$$= P_{NA} \exp\left\{-\sum_a \frac{zr_0^4}{zr_0^4+r_a^4} G(a)\right| \tag{11}$$

The successful throughput, in messages per slot from segment ***a*** becomes

$$S(a_0) = G(a_0)P(A_0 \mid r_0,\phi_0)$$
$$= \frac{\zeta q_{a_0} Z_{a_0}}{f_s T} P_{NA} \exp\left\{-\sum_a \frac{zr_0^4}{zr_0^4+r_a^r} \frac{\zeta q_a Z_a}{f_s T}\right\} \tag{12}$$

The throughput per link per second is the sum of the throughput from all its segments, $\Sigma_{a0} f_s$ $S(a_0)$.

3 Capture Probability with Site Diversity

We return to our expressions conditional on known locations of teminals. The probability $P(k_{ON} \mid A,)$ that a terminal ***k*** has transmitted an interfering packet, given that the wanted packet captures base station A, is found from Bayes rule

$$P(k_{ON} \mid A_0, \{\text{all } r,\phi\}) = \frac{P(A_0 \mid k_{ON}, \{\text{all } r,\phi\})}{P(A_0 \mid \{\text{all } r,\phi\})} P(k_{ON}) \ , \tag{13}$$

where $P(A_0 \mid k_{ON})$ is the probability that a wanted segment is received successfully, despite the knowledge that interferer ***k*** was active, but without any information on the activity of other terminals. We conditioned, for time being, on exact knowledge of terminal locations (r,ϕ). The conditional probability that the test packet captures receiver ***B*** given that it also captures receiver A is found as

$$P\left(B_0 \mid A_0, \{\text{all } r,\phi\}\right) = P_{NB} \prod_{k=1}^{N} 1 - W_{B,k} \ P\left(k_{ON} \mid A_j, \{\text{all } r,\phi\}\right)$$
$$= P_{NB} \prod_{k=1}^{N} 1 - \frac{1-W_{A,k}}{1-W_{A,k} Pr(k_{ON})} W_{B,k} P(k_{ON}) \ , \tag{14}$$

where P_{NB} is the probability that the received signal fails to exceed the noise floor at receiver ***B.*** The probability that a packet from terminal 0 captures at least one of the two base stations (A, $\cup B_0$), given the position of all terminals ***i*** ***(i = 0,*** 1, 2, $\cdots$, N), equals

$$\mathrm{P}\left(A_0 \cup B_0 \middle| \{\mathrm{all}\, r,\phi\}\right) = \mathrm{P}(A_0 \mid \{\mathrm{all}\, r,\phi\}) + \mathrm{P}(B_0 \mid \{\mathrm{all}\ r,\phi\}) - \mathrm{P}(A_0 \mid \{\mathrm{all}\, r,\phi\})\,\mathrm{P}(B_0 \mid A_0, \{\mathrm{all}\ r,\phi\}). \quad \textbf{(15)}$$

Inserting (38) and (47) in (48) gives

$$\mathrm{P}\left(A_0 \cap B_0 \,\mathrm{I}\, \{\mathrm{all}\ r,\phi\}\right) = P_{NA} P_{NB} \prod_{\mathrm{I=I}}^{N} 1 - W_{A,B,i} \mathrm{P}(i_{ON}) \ , \qquad \textbf{(16)}$$

where we introduced the joint weight function

$$W_{A,B,i} \triangle\, W_{A.i} + W_{B.i} - W_{A,j}\, W_{B;i} \qquad \textbf{(17)}$$

The $W_{A,B,i}$ can be interpreted as a factor weighing the disturbance caused by a interfering packet signal from position $\underline{x}_i$ to a reception of a data packet by terminal j at the two base stations A and B simultaneously. For the interfering traffic being a spatial Poisson process, the capture probability becomes a sum of exponential functions, viz.,

$$\mathrm{P}(A_0 \cup B_0 \mid all\ r,\phi) = \sum_{n=0}^{\infty} \frac{G_t^n}{n!} e^{-G_t}\ \mathrm{P}\left(A_0 \cup B_0\, I\, n, \mathrm{all}\, r,\phi\right) \qquad \textbf{(18)}$$

which in fact can be written as three sums, the first containing th throughput of receiver A, the second representing the throughput of receiver B and the third accounting for the 'joint' throughput.

We take the limit for N → ∞, assuming fixed offered traffic, and express the capture probability terms of $G(r,\phi)$. The result can be written in the elegantly structured expression

$$\begin{aligned} \mathrm{P}(A_0 \cup B_0 \mid r_0, \phi_0) = {} & P_{NA} \exp\left\{-\sum_a W_{A,i}\, G(a)\right\} \\ & + P_{NB} \exp\left\{-\sum_a W_{B,i}\, G(a)\right\} \\ & - P_{NA} P_{NB} \exp\left\{-\sum_a W_{A,B,i}\, G(a)\right\} \end{aligned} \qquad \textbf{(19)}$$

This equation offers a mathematical expression for the probability of capturing at least one receiver, given an arbitrary spatial distribution of the offered packet traffic, described by $G(a)$. The expression contains three terms: the first two terms are of the form of the capture probability for the individual receivers A and B respectively; the third term compensates for successful reception at two receivers simultaneously

4 Message Throughput per Link

For two-branch site diversity, the throughput of segment a_0 is

$$
\begin{aligned}
S(a_0) &= G(a_0)\mathrm{P}(A_0 \bigcup B_0 \mid r_0, \phi_0) \\
&= \frac{\zeta q_{a_0} Z_{a_0}}{f_s T} \left[P_{NA} \exp\left\{ -\sum_a W_{A,i} \frac{\zeta q_a Z_a}{f_s T} \right\} + P_{NB} \exp\left\{ -\sum_a W_{B,i} \frac{\zeta q_a Z_a}{f_s T} \right\} \right. \\
&\quad \left. - P_{NB} P_{NA} \exp\left\{ -\sum_a W_{A,B,i} \frac{\zeta q_a Z_a}{f_s T} \right\} \right]
\end{aligned}
\tag{20}
$$

A similar expression can be derived for more cooperating base station. In our computations, we considered the nearest three base stations. In the case that also a fourth base station receives messages from a particular link, mostly the common throughput, containing only duplicates, appeared to be large leaving little additional throughput. The number of messages uniquely received at base station 4 appeared negligible. We found that the computations for three base stations appeared to be sufficiently accurate (Linnartz and Westerman, 1994).

It can be seen from the above expression that for a system of given architecture, the ratio of the penetration grade ζ and the transmission interval T is a crucial parameter. The throughput of successful messages initially increases with increasing ζ/T but decreases if ζ/T becomes too large. If the penetration grade is know, the system can control T by sending broadcast messages to the probes. The optimum value of T however depends on the distance between the receiving base station and the link of interest. This will be illustrated in later sections. For a detailed theoretical discussion of the performance of wireless ALOHA nets we refer to (Linnartz, 1993).

If a link contains several segments, the total link throughput is the sum of the throughput of all segments.