Title

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Publication Date
1993-08-01

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Collecting Road Traffic Data Using ALOHA Mobile Radio Channel

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UCB-ITS-PWP-93-9

This work was performed **as part** of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

AUGUST **1993**

ISSN 1055-1417

Abstract This report proposes a spectrum efficient solution for transmitting link travel times from vehicles to a central infrastructure. The performance of an **ALOHA** mobile radio system for this application is studied analytically. The average number of new updates per minute and the expected time lapsed since the latest update of the road traffic situation in a particular street section is obtained. Results show that in an urban environment, a single (cellular) radio channel has sufficient capacity if receivers are located every 5 to 10 km.

1 Introduction

A number of Advanced Traveller Information Systems (ATIS) are being developed to broadcast traffic information to travelers [1]. Examples are U.S. Transport Advisory Radio (HAR and AHAR) and data messages added to the audio and video signals on FM and TV transmitters. The Radio Data System (RDS) system, the German Autofahrer Rundfunk Information (ARI) and the British CARFAX are examples of systems using subcarrier FM radio transmission. Such ATIS services can help motorists in finding optimal routes to their destinations and may relieve local road congestion [2]. The real-time traffic data required to generate ATIS service messages can be gathered from police and local authorities, sensors [3], weather stations and air or video surveillance. Few systems are yet operational that gather real-time road traffic data automatically. It is widely recognized that travel times between two points are more reliable than measurements of the speed of vehicles at one particular point along the road. Therefore (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. The data packets generated per vehicle typically contain only a few hundred bits and arrive infrequently. Transmission over a circuit-switched cellular telephone network would be very inefficient for this type of data traffic since call set-up times are in the order of a few seconds. On the other hand, wireless data networks mostly focus on reliable exchange of data packets which requires retransmission of messages lost in interference, noise or signal fades. In contrast to this, the application addressed here may tolerate erasure of a significant portion of the data messages. Moreover, whenever a message is erased, one would prefer in a next transmission to contain a more recent update, rather than a retry of an old message. It may not be necessary to receive updates from all vehicles, once the number of participating (probe) vehicles exceeds a certain penetration grade.

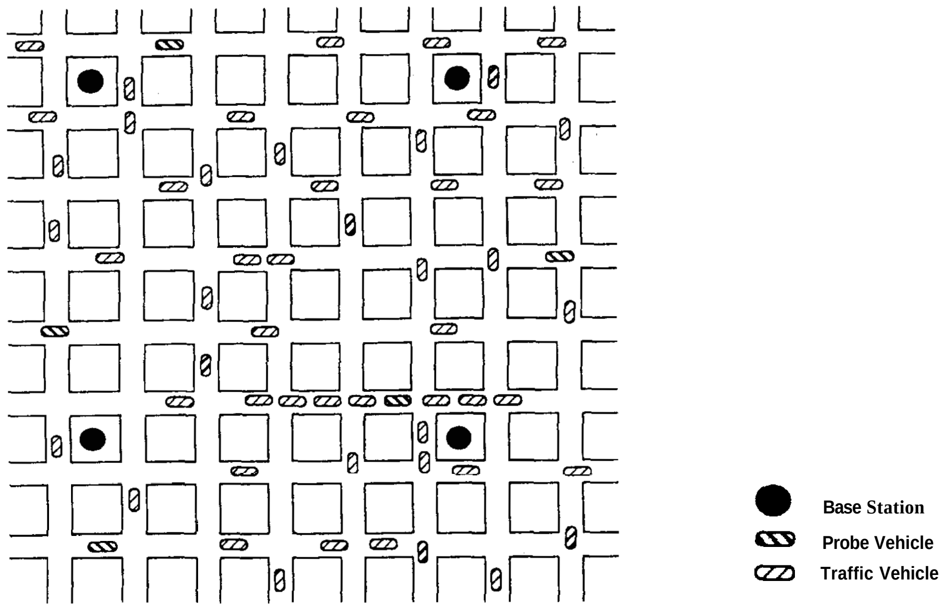

Figure 1 *Urban scenario of many vehicles travelling in the service area of an* ATM/IS system. *Multiple base station collecting road traffic data from participating (probe) vehicles.*

In this report, we study a radio system which is specially suitable for the particular characteristics and requirements encountered in collecting travel-time data and location updates from vehicles. Figure 1 illustrates the scenario of many vehicles in the service area of a radio network with many base stations. Polling these vehicles in a TDMA system requires substantial managements efforts, including transmission of synchronization signals, handovers to other base stations and dynamically updating the transmission sequence according to the changing positions of the vehicles. The overhead of the managing protocol may significantly reduce the efficiency of such network. Another extreme, which we address here, is to not coordinate vehicle transmissions at all. All vehicles transmit on the same common radio channel. All base station listen to this channel and transfer any received message to Central Traffic Data Network. This uncoordinated transmission leads to message collisions which reduces the efficiency of the network, but on the other hand the overhead for management is zero. Our analysis will show that uncoordinated **(ALOHA)** transmissions lead to an efficient and simple system.

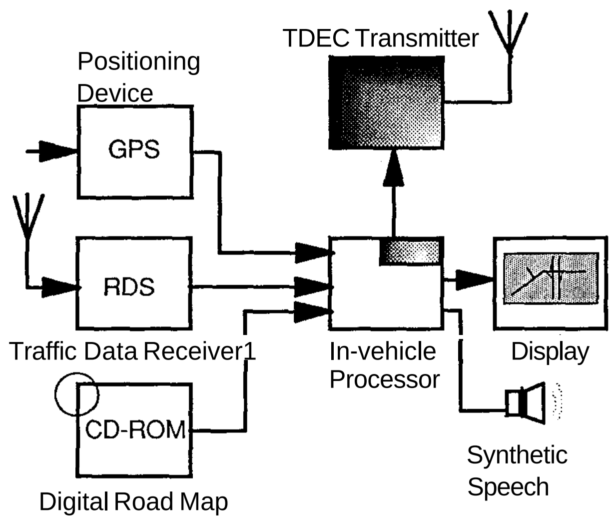

Figure *2 Block diagram of typical (commercially available) in-vehicle navigation system and* ▓ *additions / modifications required participating in* TDEC *transmissions.*

A (probe) vehicle typically contains a GPS or deadreckoning positioning instrument [4], a radio transmitter and an interface. Figure 2 shows that for vehicles already equipped with a navigation system, the additional equipment needed for the proposed system is limited to a radio transmitter and some data processing in the in-vehicle controller. The **ALOHA** scheme operates as follows: vehicle terminals 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 only the weaker signals are lost [5, 6]. However, these signals from remote terminals may capture other traffic data receivers (TDRs) at different locations. This random access channel will be called the 'Traffic Data Exchange Channel' (TDEC). This scheme allows us to use the same radio channel in a large area contiguously, thus without using different frequencies in adjacent areas, as is common practice in cellular nets. Listening traffic data receivers (TDRs), connected to a fixed backbone network, can be located throughout the system operational area. Extensive studies of such **ALOHA** radio nets have shown that error correction coding does not substantially improve the capacity [11]. Nonetheless, it is essential to optimize the error detection scheme to satisfy the requirements for the undetected error rate without increasing the packet length unnecessarily [11, 12]. Public key encryption techniques can be used to avoid misuse of the system.

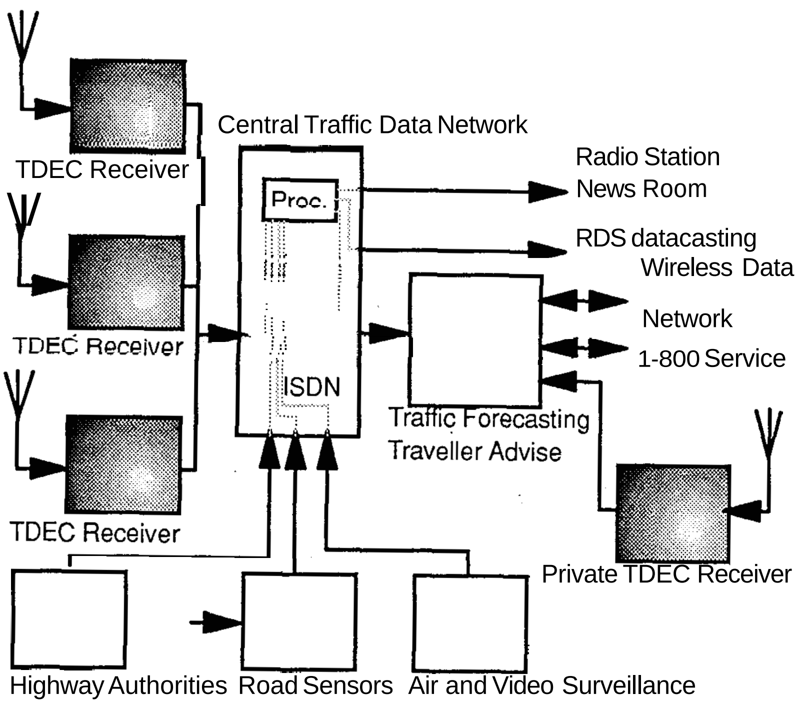

Figure 3 *Central Traffic Data Network for exchange of information between various parties involved (such as highway authorities,* **ATIS** *service providers).*

The organization of the paper is as follows: Section 2 describes the system in more detail, Section 3 describes the model for vehicle traffic in an urban area and Section **4** reviews some recent results on the performance of ALOHA in mobile radio channels. Inserting the road traffic model developed in Section 3 gives the probability that a TDR receives an update on the travel-time in a certain street section. The optimum frequency of performing a transmission is derived in section 5. Section 6 describes the spectrum efficiency and compares the single channel scheme with cellular frequency reuse patterns. Conclusions are in section 7.

2 System concept

In an entirely centralized ATIS operation, multiple TDRs collect traffic messages from a large area. If a TDR receives a traffic report, it sends this to a central traffic computer through a wired communications infrastructure, where the data is combined with information from other sources (see Figure 3). After appropriate processing, the resulting travel advisories are broadcast including, for instance, HAR and subcarrier RDS. One of the advantages of defining a wide-area standard for TDEC vehicle reports is the flexibility of choosing a scope of operation for receiving and processing link travel data from probe vehicles. We summarize a few examples to show that a migration towards a full system is possible if immediate installation of a centralized system is regarded unrealistic: once the TDEC channel transmission scheme is defined and experiments begin, participation may develop gradually as more services use the travel data.

ATIS Service Providers:

The processing of link travel data can be performed as a public service or as a commercial service offered to subscribers. Hybrid concepts are also possible. For instance a public service may provide travel advise only for a few major highways on which the congestion is of particular concern to local authorities, whereas private service providers can perform more rigorous analysis, predicting congestion using state-of-the-art data fusion techniques and novel traffic flow models.

Decentralized Autonomous Advisory Systems:

A simple ATIS system may consist of a TDR receiver, a processing unit for received traffic data, and a presentation device. Examples of presentation output devices are electronic text displays along highways, dynamically controllable road signs or speech synthesizers connected to an HAR transmitter. The receiver gathers traffic data from vehicles in its vicinity. This data is used by the processing unit to evaluate the local traffic conditions and to take actions accordingly.

On-board Vehicle Navigation:

The TDEC channel concept can also work in areas where no fixed infrastructure is available at all: Any vehicle can receive messages offered to the TDEC channel by other vehicles. This requires replacement of the RDS receiver in Figure 2 by a TDEC receiver. The received signals typically contain road traffic data from an area with a range up to a few kilometers from the receiving vehicle. The received link times may be used in combination with a CD rom onboard navigation system.

Commercial Fleet Management and Public Transit Monitoring:

The interest in Automatic Vehicle Location systems is growing, as it may enhance the efficiency of operation a fleet of commercial vehicles or the grade of service of a public transit system. Typical solutions proposed for the radio network is to poll all vehicles according to a regular scheme. Disadvantages of such schemes are the need for a central control, the waste of spectrum resources by sending out synchronisation and sequencing messages and by polling stationary vehicles. The scheme proposed here can also be used in a closed user group network. We believe that using the proposed single-channel approach with random transmissions is more efficient than polling vehicles in a cellular re-use pattern, less expensive to implement and more flexible to expand.

3 Formulation of Traffic Model

Travel times across links are, in general non-stationary random quantities. Non-stationarities exist over small time intervals (e.g. related to the phases of traffic signals) and over large time intervals (e.g. related to the peak-period congestion. Randomness occurs due to variations in driver behaviour, arrival rates, etc. In addition, travel times can vary significantly depending on turn direction and lane. This may imply that a road segment may need multiple travel time measurements, including lane and turn direction. A fairly complicated estimation procedure is needed to produce the best estimate of the link's travel time. Here we will not study these issues in detail, but focus on the radio communication network and its throughput. We address a regular grid road structure (Figure 1); an idealization of the pattern encountered in many U.S. cities. We assume N_{ns} ($^2\log N_{ns} = n_{ns}$) streets in North-South direction and N_{ew} ($\lceil {}^2\log N_{ew} \rceil = n_{ew}$) streets in East-West direction. A typical value of the grid spacing is D = 150 m, which corresponds to one twelfth of a mile. The radio system covers a total surface area $N_{ns}N_{ew}D^2$, with streets of a total length $D_{tot} = 2N_{ns}N_{ew}D$. A digital system would need at least $n_{ns}+n_{ew}$ bits to represent the grid location of each intersection of N-S and E-W streets. A fleet of N_v ($^2\log N_v = n_v$) vehicles is driving through this city according to a random pattern. The probability of passing an intersection in a given time interval is identical for all intersections and for all vehicles. We ignore the effect of any boundary of the city (n_{ns}, n_{ew} are large). A message contains a synchronisation word of n_{sync} bits, n_{er} block error control bits, an identification address (n_v bits), its current position (n_{ns} + n_{ew} bits), and a sequence of the M previous locations and traveling speed between these locations. Each link travel time is encoded in n_t bits. The total transmission time T per packet, expressed in seconds, is thus

$$T = [n_{sync} + n_{er} + n_t + (M+1)(n_{ns} + n_{ew}) + Mn_s]/r_b.$$

We give our numerical examples for $n_{sync} = 16$, $n_{er} = 16$ and $n_v = n_{ns} = n_{ew} = n_t = 8$ bits, so $T = [64 + 24M]/r_b$. The radio access protocol is unslotted **ALOHA,** but messages lost in fades or in collisions are not retransmitted. Each vehicle transmits a traffic report on average every p seconds, where p ($p >> T$) differs from transmission to transmission in order to avoid that messages from the same set of vehicles continue to collide on the random access channel. In normal operation, each vehicle transmits each travel time only once. This agrees with our assumption $p >> MD/v$.

The link travel time does not only depend on the speed of passing through street sections, but also on the waiting time at intersections. Except possibly for U.S. four-way stops, this waiting time highly depends on the turn direction and the lane choice. Transmission of a sequence of street sections ($M > 1$) helps to estimate how link travel times depend on turn directions.

4 Probability of receiving an update

We focus on one particular street section. If the number of vehicles is large (n_v is large), the size of the city is large (n_{ns}, n_{ew} are large), the number of equipped probe vehicles that pass through that street section is Poisson distributed with arrival rate λ, expressed in s^{-1}, where

$$\lambda = \frac{N_v v}{2 N_{ns} N_{ew} D}$$

A traffic message provides data on the previous $t = MD/v$ seconds. The probability that a probe vehicle that passes through the test section transmits its passage time is MD/vp. The probability that, during an interval of q ($q \gg MD/v$) seconds, j vehicles transmit their speed in this particular section is Poisson distributed with mean $q\lambda_t$, where

$$\lambda_t = \frac{\lambda}{p}\frac{MD}{v},$$

The probability of receiving no update is equal to the probability that none of the probe vehicles sends a message plus the probability that of those vehicles which do transmit their link travel time, no transmission reaches a base station. Thus, the probability of no update is exp $\{-q\lambda_t Q(r)\}$. Here $Q(r)$ is the probability that the data packet is received correctly over the fading **ALOHA** radio channel, which is a function of the distance r between the street section and the receiving base station [5]. Figure 4 presents the probability of no update from a segment versus the number of probe vehicles per unit of surface area ($\lambda_v = N_v/N_{ns}N_{ew}D^2$) under the assumption of perfect communication, i.e, $Q(r) = 1$ for any r. The assumption of perfect communication implies that if a probe vehicle makes a transmission, that transmission will be successful and be received by the base station. Thus, the chance of collisions with other probe vehicles' transmissions is ignored under this assumption.

To determine $Q(r)$ we first compute the total interfering packet traffic on the radio channel. The N_v terminals generate Poisson traffic with mean intensity λ_i ($\lambda_i = N_v/p$) packets per second, uniformly spread over an area of size $N_{ns}N_{ew}D^2$. So the average number of data packets transmitted per packet time T and per unit of area, G_0 is

$$G_0 = \frac{N_v T}{p N_{NS} N_{EW} D^2} = \frac{\lambda_v T}{p}$$

The probability of successful transmission $Q(r)$ depends on G_0, the propagation environment, the modulation and coding technique. Here we follow the analysis described in [5]. For a Rayleigh-fading channel, the probability of successful reception for a test packet from distance r was shown to appear as a weighing of the Poisson intensity $G(x)$ of the interfering packet traffic at distance x by $zr^\beta/(zr^\beta + x^\beta)$, with

$$Q(r) = \exp\left\{-K\int_0^\infty \frac{zr^\beta}{zr^\beta + x^\beta} 2\pi x G(x)\, dx\right\}$$

with $G(x)$ expressed in packet arrival per packet time per unit of area. The constant K is equal to 1 for 'slotted' **ALOHA** and equal to **2** for 'unslotted' **ALOHA.** In the case of slotted **ALOHA,** messages may only be transmitted in predefined (but not vehicle-specific) time slots. In slotted **ALOHA,** message transmissions either overlap completely in time or do not overlap at all. This avoids loosing packets due to partially overlapping transmission times. It substantially enhances the throughput of successful messages.

In the above expression, z is the receiver threshold, i.e., the signal-to-interference ratio above which successful reception is likely to occur ($z \approx 4$ .. 10), and β is the path loss exponent. Typically, $3 < \beta < 4$ in UHF propagation. If the path loss exponent of $\beta = 4$ is taken, and an infinitely extended network is assumed ($G(x) = G_0$ for any $0 < x < \infty$)

$$Q(r) = \exp\left\{-\frac{\pi^2}{2} K\sqrt{z} r^2 \frac{\lambda_v T}{p}\right\}$$

The total throughput per the base station, expressed in packets pet packet time, is

$$S_t = \int_0^{\infty} 2\pi r G_0 \, Q(r) \, dr = \frac{\beta}{2K\pi z^{2/\beta}} \sin\frac{2\pi}{\beta}$$

Despite the adverse nature of the 'poor' mobile radio channel, this throughput is well above the throughput $S_t = G_t \exp\{-KG_t\} \leq 0.36/K$ for wired ALOHA channels, where G_t is the total offered traffic, irrespective of the distance from which the messages are transmitted. Even though the above total throughput was derived for an infinitely extended network, thus with unbounded total offered traffic ($G_t \rightarrow \infty$), the throughput is nonzero for the TDEC network. For $\beta = 4$ and $M = 1$, this gives a throughput 86 travel-time reports per second per base station, but some packets may be received at multiple base stations simultaneously [6]. For larger M, the efficiency increases significantly, to a maximum of 320 travel-time reports per second, unless packets transmission time exceeds the typical non-fade duration of the mobile channel [5, 6]. This result is independent of p and M, but with increasing transmission density (large p) the base station will only receive messages from nearby vehicles. Signals from remote vehicles are not likely to capture the base station. Hence, we wish to optimize the number of transmission per vehicle to achieve a fair distribution of received messages over the service area.

Traffic reports arrive from *a particular street segment* at distance r with aggregate arrival rate

$$\lambda_t Q(r) = \frac{M\lambda_v D^2}{p} \exp\left\{-\pi^2 \sqrt{z} r^2 \frac{\lambda_v T}{p}\right\}$$

reports per second. Here the packet transmission time is a function of M ($T = T(M)$). The averaging time needed to obtain a good estimate of the statistical behaviour of link travel times may be significantly larger than MD/v. In such case, relatively large values of M will be optimum provided that the transmission time remains smaller than a typical nonfade period. The objective may be to optimize the packet throughput per unit of area for locations with poor propagation.

Another objective can be to minimize the average time EW elapsed after the latest reported passage through a street section is the time since the last update plus the time expired before the vehicle transmitted the report. One finds

$$EW|r = \frac{1}{\lambda_t Q(r)} + \sum_{m=1}^{M} \frac{m}{M}\frac{D}{v} = \frac{1}{\lambda_t Q(r)} + \frac{(M+1)D}{2v}$$

Next we will minimize this time for a worst case location by optimizing the parameters p and M .

5 Optimum transmission scheme

The optimization of the average time between two updates $W(M,p,r)$ for an street section at distance r requires that $dW/dM = 0$ and $dW/dp = 0$. This gives

$$M_{OPT} = \sqrt{\frac{4\pi^2 v\sqrt{z} r^2 e(n_{sync}+n_{er}+n_v+n_{ew}+n_{ns}+n_s)}{r_b D^3}}$$

and

$$p_{opt} = \pi^2 \sqrt{z} r^2 \lambda_v T$$

Since M_{opt} is proportional to $\sqrt{v}$, probe vehicles which travel at a high speed should store more sections before transmitting, rather than transmit more frequently (*p* is independent of *v*). If one adopts *unslotted* ALOHA, it is possible to allow vehicles to transmit messages of different duration, depending on their speed *v*. Typical values of M_{opt} are not very large (eg, with $r = 6$ km, $M_{opt} = 7$).

Figure 5 graphs the probability of no update from a street segment against the probe vehicle density. Once a certain probe vehicle density is reached, any increase of the density will not give more updates: the capacity of TDEC channel has become the main limitation to the arrival of more traffic messages. Figure 6 presents the average time between two updates on the same street section versus the probe vehicle density. After a certain probe vehicle density is reached, any increase of the density will not reduce the delay. The delay also depends on the distance. As the distance is increased, there is a noticeable drop off from the perfect communication performance. This means that given a minimum required update arrival rate, an upper bound on the maximum distance between base stations can be determined.

6 Spectrum Efficiency

The spectrum occupation of TDEC is small even though a very large number (theoretically infinite) of probe vehicles can participate. The systems uses only a single radio channel throughout the entire operation area. This is in contrast to cellular (telephone) networks and broadcast transmitter networks, where a frequency used in one area (or "cell") can not be reused in adjacent areas because of excessive interference. The number of different frequencies is called the cluster size and is denoted as C. To compare the spectrum usage of our system with a cellular telephone network, we normalise the spectrum use of cellular telephone calls to unity and relate this to the spectrum occupation of the ALOHA system. In order to make a fair comparison, two effects need to be taken into account: the cluster size of the cellular telephone net and the erlangian trunking efficiency [7]. For A_c erlang of telephone traffic per cell on N voice channels, the blocking probability is B. Typically, a blocking probability of 1 or 10% is required. The normalised spectrum efficiency is $SE_{tel} = A_c(1 - B)/(C\,N)$ erlang per base station per cellular channel. Typically, $A_c(1 - B)/N$ is on the order of 0.5 to 0.9, while C is 7 or 9. Hence, SE_{tel} is on the order of 0.10 erlang per cell area per channel. Since each frequency in a cell area supports roughly 100 to 200 reports per second, rather than 0.1 erlang, the comparable spectrum usage cost of per travel-time report is about $10 \cdot 10^{-6}$ time the per-minute rate of a cellular telephone call.

As the radio spectrum is increasingly becoming a scarce resource, the collection of traffic data from probe vehicles may have to share a frequency band with other IVHS services, e.g. downlink transmission of travel advise from base stations to vehicles. It can be shown that for packet switched data communications, splitting this frequency band and employing a cellular frequency reuse is pattern (say with C = 7 or 9) is less efficient that intermittently operating all base station on the same frequency. This also provides the opportunity to open certain time windows for the application addressed in this paper: random transmission of link-travel times.

7 Concluding remarks

Integrated ATIS systems gathering probe vehicle data and broadcasting transportation advice are studied for instance in the European SOCRATES Project [2] and the Californian PATH program. This paper studied the performance of a mobile radio system collecting road traffic data from probe vehicles and gave a optimization of the transmission scheme. The proposed TDEC concept can be used for the travel-time data gathering without loosing a significant portion of the messages if each base station serves an area with a radius of up to $R = \mathbf{4}$ or 5 kilometers. However, for distances larger than, say, 6 km and more than 1000 probe vehicles in this area, the capacity of the radio channel limits the performance of the system. In such case additional TDR receivers may be installed to increase the number of travel-time messages received from each street section. Our model assumed a uniform distribution of traffic of a dense street pattern in a wide area. In a more realistic situation most traffic will be concentrated on a few arteries. Travel times on these particular streets are more important but fortunately most TDEC messages originate from densely used street sections. In such case, our uniform model gives relatively pessimistic results.

8. Acknowledgement

This report has been prepared in cooperation with the State of California, Business, Transportation and Housing Agency, Department of Transportation, and Partners for Advanced Transit and Highways (PATH). The contents of this paper reflect the views of the authors, who are responsible for facts and accuracy of the data presented herein. The contents do not necessarily reflect official views or policies of the State of California. This paper does not constitute a standard, specification or regulation.

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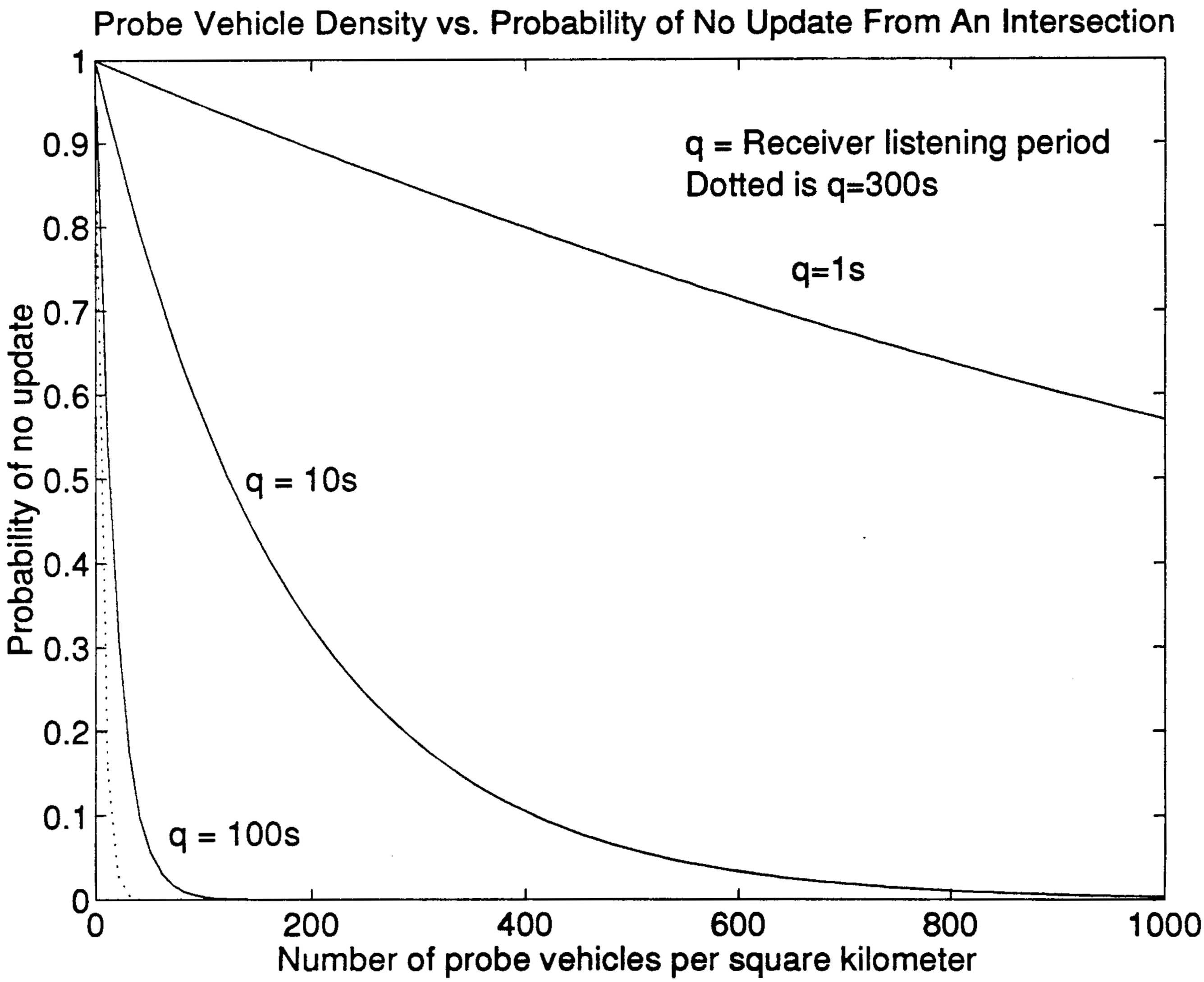

FIGURE *4 Probability of no probe vehicle passing through a certain street section during period q, versus number of vehicles per square kilometer. Probability of receiving no update in a system with perfect communication* ($Q(r) = 1$, $M = 1$, $p = D/v$)

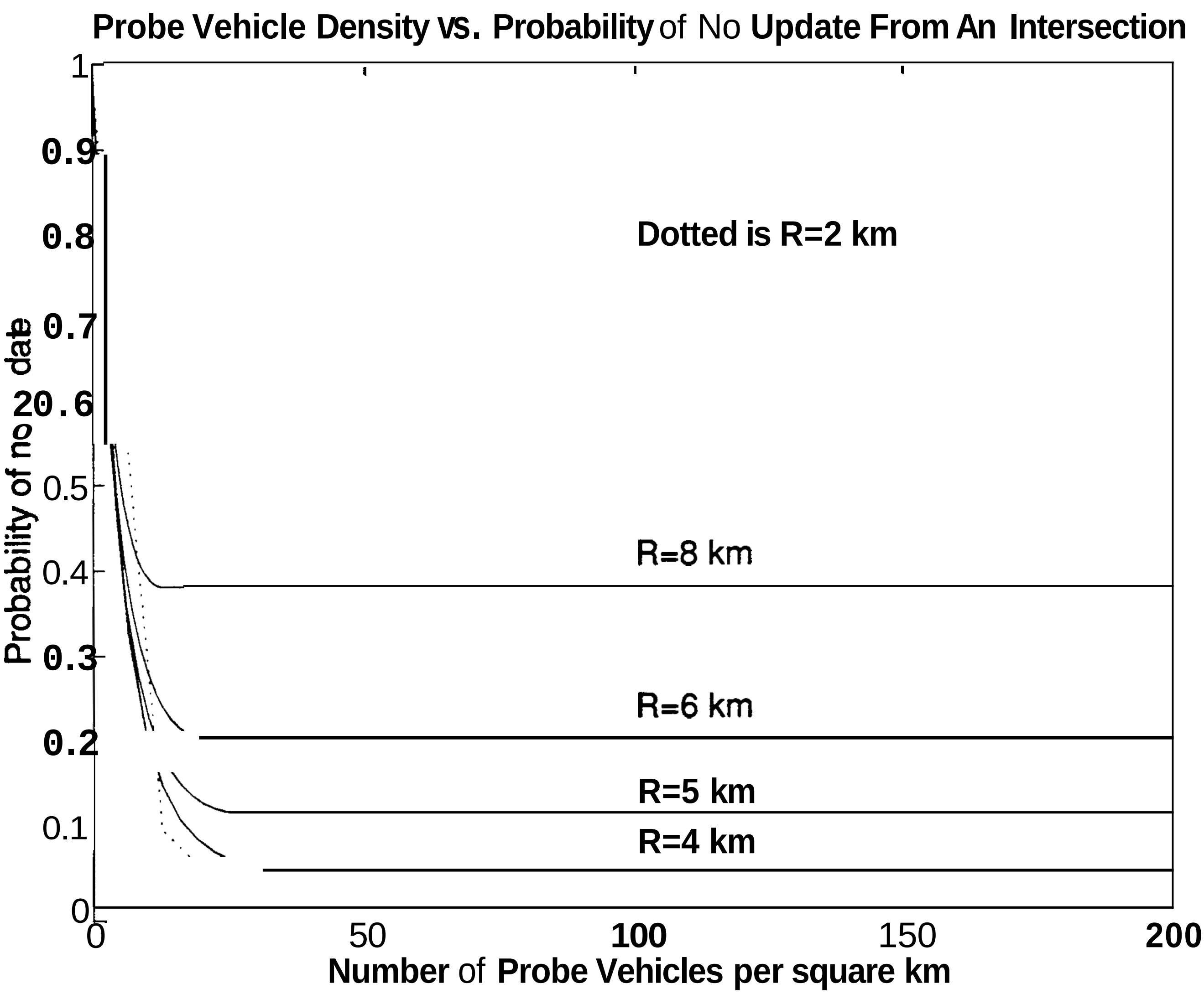

FIGURE 5 *Probability of no update from a street segment at distance r versus probe vehicle density. UHF path loss* $\beta = 4$. QPSK *transmission* [9] *with* $r_b = 48$ kbit/s. *Receiver threshold* $z = 10$. *City grid spacing* $D = 150$ m. *Transmission scheme: M, p optimized for each distance and probe vehicle density plotted. Packet length* $T = (64 + 24\,M)/r_b$ sec.

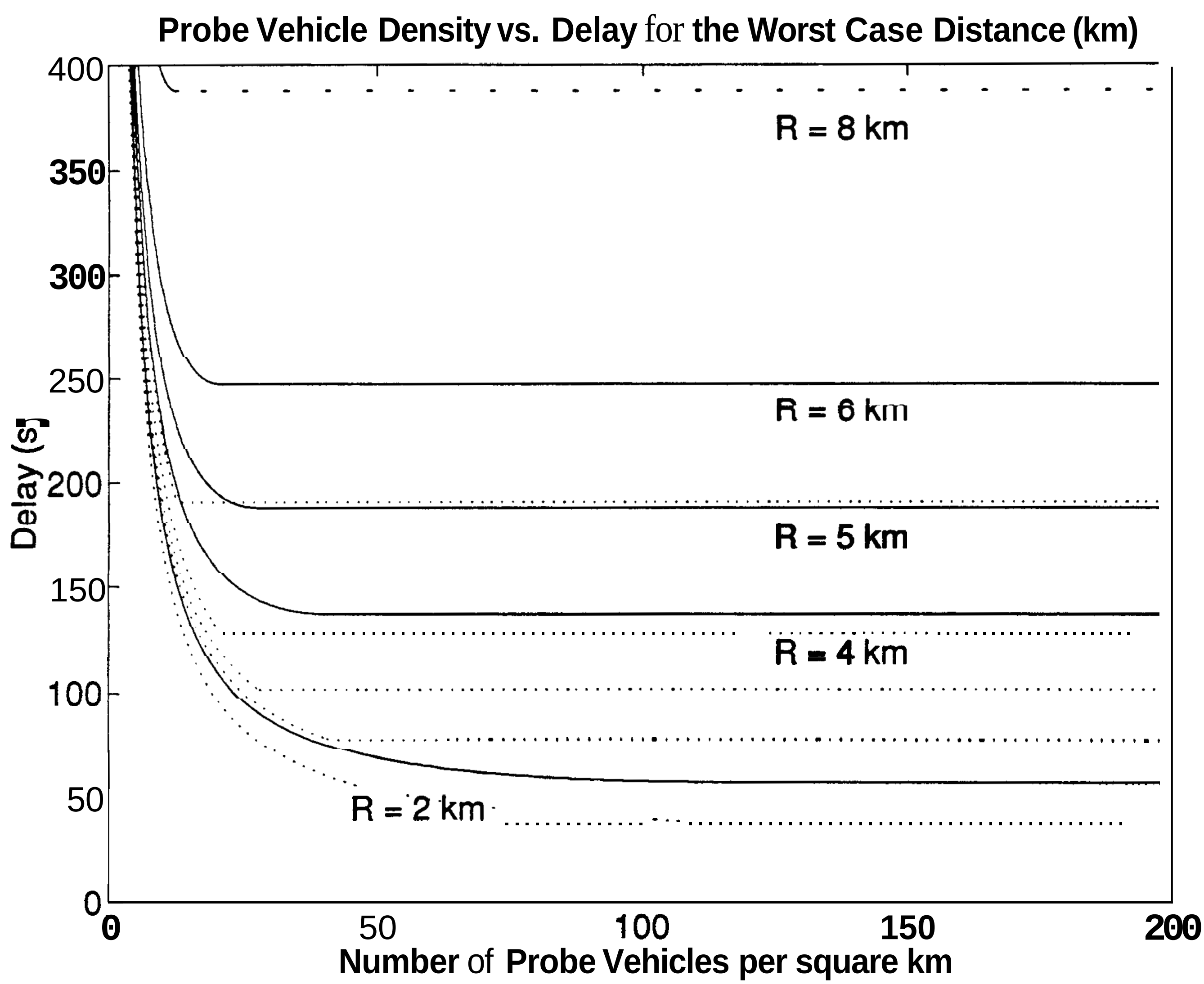

FIGURE 6 *Average time elapsed after latest arrival of update versus probe vehicle density for various distances. (see* **FIGURE** 5 *for parameters)*