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Message Volumes for Two Examples of Automated Freeway

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Message Volumes for Two Examples of Automated Freeway

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ABSTRACT

In previous work, two very different complete specifications of automated freeways have been constructed and shown to conform to safety criteria. These specifications are here put to a different purpose, which was not planned when they were conceived. In this paper, calculations are made of the volume of messages transmitted between vehicles or between vehicles and the infrastructure, in order to estimate the demand of AVCS systems for frequency allocations.

The calculations made are of message volume only: the choice of transmission protocol and the allowances that must be made for retransmission of garbled messages are not discussed. Nor, although the two systems could be said to “span the range” between purely vehicle-borne intelligence and purely infrastructure-borne intelligence, should these conclusions be assumed to apply to all systems.

In both cases, the apparent demand for transmissions of control data, if unconstrained by technological simplification, is found to be impracticably large. However, in each of these cases, means exist by which the demand can be reduced to 1 - 2 kbaud. There is also a demand for bandwidth for emergency messages. It is small, but the importance of quick reaction to such messages may make it desirable to reserve a channel for them alone.

In a full-scale emergency situation, messages are few and short. The maximum demand arises, in each case, in fault conditions of rather less immediacy. The critical case seems to be the situation where a failed vehicle causes a length of automated lane to close. If delay and complexities are to be avoided, it is necessary that all vehicles in the affected lane change lanes rather promptly. The resulting flurry of messages represents the maximum demand.

In both cases this volume of demand translates into a requirement for between 10 and 15 kbauds. This figure may not apply generally. There could well be other systems, as yet unspecified, that have much larger or smaller demands.

INTRODUCTION

Recently, two conceptual designs for an automated freeway have been published (I, 2). They are complete -- that is, they specify system behavior in fault conditions as well as in normal operation. They were constructed to provide examples on which to test the applicability of certain forms of analysis to the demonstration of safety. This paper, however, is not concerned with safety, but with message volume. The two previous designs are used to provide a basis for calculations.

In this paper the volume of digital messages required by the designs described in (I) and (2) is calculated. These figures may be sufficient to give indicative values for the demand for bandwidth. The figures are for two very different systems each of which has its maximum demand for message volume in similar fault conditions. Also, the total volumes of demands are similar. It may be plausible that the similar figures apply to all reasonable designs. We cannot say on the basis of the work here. However, the figures do apply to particular systems that are known to be complete and safe: the designs take account of fault conditions.

One of the designs considered (I) has a maximum amount of intelligence within the vehicle: we shall refer to it as a **vehicle-intelligence** (VI) system. The other (2) is an **infrastructure-intelligence** (II) system. These designs are extreme examples of VI and II systems - there is room for intermediates. We shall not, in this paper, explain the architecture or mode of operation of either system. Consequently, some terms of art will not be defined. The architecture contains several "layers" or "levels," and we shall refer to these without defining them. In both systems, vehicle movement is organized in platoons.

In the USA, frequencies are, by law, allocated over a wide range of the electromagnetic spectrum. It is illegal to transmit on a frequency allocated to another user. Frequencies are in short supply, and as a newcomer, IVHS is bidding for a very small amount of remaining spectrum. Only in the infra-red is there no problem; but the bulk of the competition with which IVHS is concerned is for frequencies in the range 50 Mhz - 1 GHz, and this is predominantly of value for transmitting messages. (We call this frequency range the **prime range**.) In this paper, the demand for message volume will be expressed in bauds (= bits/sec.). Allowance will be made for message-start bits and check bits, but there will be no quantitative discussion, the translation into bandwidths allocated, or mention of the additional bandwidth needed for retransmissions with different access protocols.

In these systems, some information is determined by direct measurements that may need frequency allocations, but are not messages. The main example is the measurement of separation between vehicles in a platoon and their relative velocity, which will probably be done by some form of radar or ultrasonics. The frequency will be outside the prime range, and it will not be discussed further. Indeed, we shall generally take the view that if

a function can be discharged by the use of frequencies outside the prime range the problem is partially solved. Bit-rates, however, will be identified.

After the calculations reported in this paper were complete, the author read Streisand (3), which is concerned with a VI system. In general, the part of Streisand's work that addresses message volumes agrees with what is said here, allowing for some **within-**uncertainty differences in the values of the parameters used. However, she does not consider all the technological possibilities, some of which can have large effects. The burden of Streisand's work is concerned with the selection of transmission protocols for different parts of the system.

Types of Messages

There are several types of messages that pass to or from vehicles in these systems. Each type has different frequency and reliability requirements:

- In each case, as previously mentioned, there is a device operating outside the prime range that measures the separation and relative velocity of each vehicle from the preceding one in a platoon. Differences between successive relative velocity readings may be used as a proxy for relative acceleration.
- The messages that enable control of a vehicle in a platoon include regular statements of the velocity and acceleration of the lead vehicle of the platoon, and may include some other data, depending on the design concept. In the language of Varaiya and Shladover's (4) architecture, these are regulatory-level messages. They are **time-**critical, and need to be updated many times every second.

The designs are such that failure to update these messages is not an immediate cause of danger, unless the communication failure is compounded by other faults. Indeed the rate of repetition is determined by considerations of platoon stability, rather than safety. Nevertheless, repeated failure to pass these messages would result in a violation of safety criteria. VI systems have independent means of checking on the integrity of their own equipment ("looping"): if expected messages are not received, they report a fault in the infrastructure to the system. II systems will normally interpret such failure to communicate as evidence of failure of communication equipment, and will take action accordingly.

If a message requires the vehicle to brake to a stop, it is clearly safety-critical. For this reason, in the II system, whenever a vehicle's maximum speed changes, the instruction is duplicated. The instruction is transmitted, not only in the **regulatory-**level stream of updates, but also as a special platoon-level message. (For further detail, see (2)). Thus, two faults are required before a message to a single vehicle to brake to a stop is not received.

- Messages that advise a vehicle to change lane, to enter or leave the automated lanes (ALs), or to join or leave a platoon usually come from the platoon level of the architecture. These messages originate in the infrastructure in II systems: in VI systems, they are vehicle-to-vehicle messages. A few such messages, especially in VI, originate at link level.

Failures to receive such messages are not safety-critical, except for the platoon-level maximum-speed message mentioned above. However, if messages are not acted on within 1-2 seconds, the system will snarl up. Cars will not reach their destinations, and congestion levels will rise. What is liable to produce hazards, however, is the interpretation of a garbled message as a valid one of the wrong type, or the action by one vehicle on a message intended for another.

In VI systems, information must also pass from the infrastructure whenever a vehicle changes lane. For example, the new lane may have a different operating mode. In the II system, this information is used at the roadside to compose regulatory-level instructions. In the VI system, the data must be supplied to the vehicle for this is where the regulatory-level instructions are generated.

- Emergency messages, like “Everybody brake to a full stop,” “lane x is blocked at milepost y,” or “I, vehicle z, have hit something and will very soon be an incident” are few and simple. They may have a channel of their own; or in II systems, they may simply preempt all other messages. Normally they need to be acted on within a few tenths of a second. Clearly, they are safety-critical.
- There may also be all sorts of messages that do not affect vehicle control. These range from data about parking to phone messages. They do need bandwidth, but they are not part of automated freeways. They will therefore be ignored here.

Message Format

A message must contain elements besides the primary content data. We assume a format as follows:

- **An introduction** (INT). This gives notice that there is a message coming with which the recipient should get into synchronization to receive. Most random-access protocols seem to need a 16-bit INT. Presumably, if the messages are strictly timed so that the recipient can use its internal clock for synchronization, a shorter INT (perhaps 4 bits) would suffice. We shall use the 16-bit figure here, but refer to the other possibility later.
- **A message type** (MTY). Each type will have its own data-record structure, and the receiver needs to be forewarned about the interpretation it will need to execute.

- A source *address* (SA) and a *destination address* (DA). Not every message type will need either or both. In II systems, messages to or from the infrastructure have one address defined by MTY. Many VI messages are addressed to any vehicle in range. Most emergency messages need neither address in full detail: they apply to “all vehicles in lane x.”

The length of these fields requires discussion. If a unique vehicle identity is used, then we must design for the ultimate situation, in which most vehicles are equipped. Even if we assume that vehicles coming from other countries will be relabelled in the U.S., some 30 bits would be needed to provide a unique ID for every vehicle. This is very wasteful of bandwidth, since all that is needed is to ensure that a label is unique within the range of one transmitter. Another possibility is that a vehicle should be given a temporary ID at each entry to a system (i.e., to a metropolitan district). For a large urban system of the future, containing perhaps 5,000 lane-miles, this would require 20 bits. However, if the label changed every time the vehicle changed lane or block, 8 bits would suffice. In some cases, this could be a platoon name and a position. Since a message often has to contain lane number and block number as parameters (they need some 9 bits), this looks to be a superior scheme of addressing. We shall assume 8 bits as address length, with 9 more for lane number and block number if needed.

- *The content* (CON) of the message. Again this may be absent, for some messages carry all the information needed in MTY. In others, some parametric value must also be passed along.
- *Parity-check bits* (PAR), which enable the validity of the message to be checked. PAR often consists of 8 bits; there is no reason to change this here.

Thus, the number of bits in a single message is as follows:

$$\text{INT} + \text{MTY} + \text{SA (if needed)} + \text{DA (if needed)} + \text{CON} + \text{PAR} = \\ \text{SA (if needed)} + \text{DA (if needed)} + \text{CON} + 32$$

for, as explained above,

$$\text{INT} + \text{MTY} + \text{PAR} = 32.$$

System Parameters

In this section, we need to remember that frequency allocations and bandwidth will not be easy to change. We must, therefore, design for the largest systems that we can conceive in the future. It is perhaps conservative to assume a maximum capacity of 6000 veh./hr (three times present).

Vehicles per lane-mile. If a section of a lane contains stopped vehicles, further entry to that section is inappropriate. In degraded modes of operation, speeds may fall to 30 mph. At 30 mph, at full capacity (6000 vehicles per hour) there are 200

vehicles/lane-mile; In wet weather, the coefficient of friction that can be relied on can be as low as 0.25, implying a minimum stopping distance at 60 mph of some 200 yards. If a system design requires that each platoon should be able to communicate with the leader of the preceding one so as to keep a safe headway, minimum transmission ranges of 250-300 yards are needed. This has implications for both bandwidth re-use and power control.

Lanes per freeway. Current freeways range up to 6 lanes in each direction. Let us assume that two of these are reserved for driver-controlled traffic (such traffic can hardly be excluded totally) and that one more, though automated, is not reduced in width because it is intended for buses, trucks, and other wide vehicles. The other three, because of the precision of automatic steering, can be replaced by five automated lanes, making 12 automated lanes in all, counting both directions.

Requirements for Control Data: VI System

In the VI system considered (2), the distance and relative speed of the vehicle ahead are measured by the forward sensor, and do not need bandwidth in the prime range. The following data does, however, need to be transmitted for control in a platoon:

"Down" platoon

From front to rear of the platoon, a control message is passed from the rearward transmitters of one car to the forward receivers of the next. It contains:

Platoon ID and lane number. Crosstalk between platoons is possible, and has to be eliminated: 8 bits for the platoon ID, plus 4 for the lane number, equals 12 bits.

Platoon leader's speed and acceleration. This data must be transmitted to all other vehicles in a platoon. Precision needed is not yet known. We shall assume here that 8 bits are sufficient for each. This gives ± 0.25 mph on speed (perhaps ± 0.1 mph on difference from target speed), $\pm 1\%$ on acceleration.

Sender's position in platoon. This will replace the need to have an SA or DA in the message. 5 bits.

Platoon size. The communicator fault detection process requires that this data be available at all times. 5 bits.

In total, the "down" message will require $32 + 38 = 70$ bits.

"Up" Platoon

The confirmatory response is passed to the vehicle ahead only. It needs only the ID parameters: platoon number, lane number, and position. Thus it contains $32 + 17 = 49$ bits.

Bandwidth for VI System

The repetition rate of this data depends on the rate at which it is needed to **update** the platoon leader's speed and acceleration. Some recent simulation work by **McMahon** and Swaroop (**unpublished data**) indicates that 3-5 Hz is sufficient. Current trials in California show 20 Hz to be adequate. The parameter is clearly critical, but, as yet there is no conclusive information. An arbitrary decision has been taken to use 5 Hz as the central value in this work.

Minimum transmission range is set by the requirement that messages can be sent reliably by the platoon leader to the last vehicle of the preceding platoon, even if the minimum platoon spacing has been extended to 250 or even 350 meters because of rain, snow, or ice. Therefore, a vehicle must have a transmission range of at least 500 meters. In good-weather spacing this could include 4 platoons both upstream and downstream of the transmitting vehicle in each of 12 lanes. Thus we would need:

$$\begin{array}{ccccccc} (70 & + & 49) & \times & 20 & \times & 8 & \times & 12 & \times & 5 & = & 1.2 \text{ Mbauds} \\ \text{bits/} & & & & \text{vehicles/} & & \text{platoons/} & & \text{lanes} & & \text{messages/} & & \\ \text{message-} & & & & \text{platoon} & & \text{lane} & & & & \text{sec.} & & \\ \text{vehicle} & & & & & & & & & & & & \end{array}$$

The mechanism of message passing within a platoon means that time-multiplexing is automatically achieved here. Between platoons, automatic channel allocation by **carrier-sense multiple access (CSMA)** could well be the appropriate protocol.

Reducing the Demand for Bandwidth: VI System

Over half of each transmission consists of **INTs**. This could be halved, through synchronization via previous signals. However, the previous signals are not necessarily being analysed by the following vehicle, and this may not be practical.

It would be possible, at some expense, to use infra-red to transmit the leader's speed and acceleration. This could be extended to include some other messages. Under these conditions, there would be no demand in the prime range for radio messages at the regulatory level. However, the transmitters and receivers would have to be retained, because **infra-red** is not satisfactory for inter-platoon communication.

A more promising possibility is to control the power of the transmissions, so that intra-platoon messages are transmitted at much lower power than inter-platoon ones. For intra-platoon use, a range of no more than 8 meters is needed, allowing for gaps in the platoon, when vehicles enter and leave. It is possible for low-intensity messages to be ignored, so that even if some signal carries farther than its designated range, it contributes to noise as opposed to garbling a concurrent message of greater intensity. Under these conditions, a maximum of 3 vehicles/platoon and 3 lanes need be considered, giving a bandwidth of some 10 kbauds. If there were sufficient directionality in the signals, the signal would not be detected in adjacent lanes. If it turns out that a vehicle reliably shields the one behind it, the demand would come down to 1 kbaud.

Requirements for Control Data: II System

The infrastructure-intelligence system that we are considering is the one described in (2). In this II system, the control data includes:

Road to vehicle

Lane # of vehicle addressed. This system uses low-power transmissions from the side of the lane to vehicles. The infrastructure transmitters are extended along the length of a block. Renaming platoons as they cross block boundaries avoids confusion between blocks. If the transmitters are truly continuous and centrally placed, like the leaky cables used to transmit to railway vehicles in tunnels, then ranges of 1-2 meters suffice, and transmissions will not extend beyond one lane. Another possible configuration has many transmitters ranged along the lanes, perhaps 20 to 40 meters apart. In this case a (4-bit) lane number is needful.

Distance to vehicle ahead, and relative velocity and acceleration. As mentioned above, the on-vehicle sensors obtain this data. It does not have to be sent from the roadside.

Speed and acceleration of the platoon leader. As in the VI case, we need 16 bits here.

Maximum speed, target speed. These are not transmitted every time, but only when there is a change. But we shall need 12 bits in the message (there is no gain in having a **variable-length** message) in any case.

Message " field

This is an indication that a message is waiting to be transmitted. The roadside equipment will queue and prioritize messages to each vehicle. If the "message-waiting" bit is set, the platoon level on the vehicle is stimulated to use its separate channel to interrogate the road about the message that is waiting. If there is more than one message, the second in priority is sent on the following cycle, provided the first was transmitted successfully. One bit will suffice.

Thus, a control data message from the road will contain $32 + 8 \text{ (DA)} + 33 = 73$ bits, except for the platoon leader, when there will be 57.

Vehicle to road

Lane number of vehicle sending. The argument is the same as that above. 4 bits.

Distance to vehicle ahead. This is required as a safety check in this II design. 6 bits.

Lateral control variable. Again, this data is transmitted to enable a check to be made of the performance of the on-vehicle control systems. 4 bits.

Own speed and acceleration. Only platoon leaders send this data. 16 bits.

Check bit. Previous message received satisfactorily or not. Basically here, one relies on frequent repetition of the data to avoid the problems of garbled messages. There is no repeat-message protocol. If there are repeated failures to receive, or to respond, emergency action is taken by the platoon-level roadside controllers.

Thus platoon leader's control data message will contain $32 + 8 \text{ (SA)} + 31 = 71$ bits, while the platoon members need 55 bits. In each case the total exchange consists of 128 bits.

Bandwidth for II System

A repetition rate of 5 Hz is taken here. The argument is the same as for the VI case.

The other factors affecting the bandwidth required are the number and length of lanes containing vehicles that may interfere. If transmission ranges are kept down to 1-2 meters there will be two such lanes. If there are discrete transmitters and receivers, 10 meters may be a minimum, giving six lanes. The maximum is 12 lanes. We shall use the last figure as the central value. We shall assume a maximum block length of 1.5 miles, giving a maximum of 300 vehicles/lane/block.

Interference is most simply avoided here by the use of time-division multiplex. Only one vehicle, out of the whole array in range, will be addressed at once. Thus we get a transmission rate of:

$$\begin{array}{ccccccc} 128 & \times & 300 & \times & 12 & \times & 5 & = & 2.3 \text{ Mbauds} \\ \text{bits/} & & \text{veh./} & & \text{lanes} & & \text{times/} & & \\ \text{veh.} & & \text{lane} & & & & \text{sec.} & & \end{array}$$

This is a high rate, and is not realistic.

Reducing the Demand for Bandwidth: II System

First, half the bits passed are in INT fields. Since the messages are precisely timed, each vehicle could use the preceding vehicle's exchange to synchronize itself. This would reduce the demand by a factor of two or so. Next, if the proposal of Hitchcock (2) is followed precisely, all transmissions are so low-powered that they are not overheard in an adjacent lane. If they are not also directional they will be heard in the lane behind the transmitter, so this will reduce demand by a factor of 6. Together this would reduce the demand to 200 kbauds.

A second possibility is to arrange that the platoon leader's speed and acceleration are passed down the platoon by other means, such as an infrared communicator. The lateral control variable and headway still need to be passed about twice a second, so these two improvements give a factor of three or so, at extra cost. All together we are now down to 60 kbauds.

One can also insert high directionality into the transmitters, so that there was communication only in a narrow beam at right angles to the road. All vehicles in the beam would be addressed simultaneously. Time division multiplexing might be replaced with some other multiple access protocol. The demand, without avoiding transmissions across 6 lanes, is now reduced to 0.6 kbaud. Admittedly, this method does assume that one knows in which beam each vehicle is located. One knows where it was half a second previously, and how fast it was moving. The scheme does need control software, but there is clearly no great difficulty. High directionality of this kind can probably only be achieved outside the prime range.

Platoon-level Messages: VI System

In a VI system, a certain amount of system data has to be transferred at platoon level. This consists of data like the mode of each lane, and preferred speed and platoon sizes in it, the position of the next gate, and so on. (In a II system this data is used at the roadside to decide what instructions to pass to the vehicle, and does not need to be considered separately.) In the VI system considered, this information is passed by the gate transmitter as each vehicle passes through it. A vehicle will change lane, and so pass through a gate, perhaps 10 times in an average quarter-hour journey segment on the automated freeway. If full range transmission is employed, and transmitter range contains 4 gates per lane, we arrive at the following equation:

$$\begin{array}{cccccc} 60 & \times & 1 & \times & 3 & \times & 12 & \times & 10/(15 \times 60) = 24 \text{ bauds} \\ \text{bits/} & & \text{message/} & & \text{gates/} & & \text{lanes} & & \text{times/} \\ \text{message} & & \text{gate} & & \text{lane} & & & & \text{sec.} \end{array}$$

A higher message rate arises from the exchanges between vehicles that accompany a lane change. In the particular system considered, a lane change will normally be preceded by a vehicle's splitting out from a platoon. Often it will be followed by a merge to another platoon. This requires an average of 12 messages between vehicles in different platoons, at an average of 50 bits each. We may assume that a vehicle will make 10 lane-changes in an average quarter-hour journey.

$$\begin{array}{ccccccc} 50 & \times & 12 & \times & 200 & \times & 0.3 & \times & 12 & \times & 10/(15 \times 60) \\ \text{bits/} & & \text{messages/} & & \text{vehicles/} & & \text{miles} & & \text{lanes} & & \text{lane-change/} \\ \text{message} & & \text{lane-change} & & \text{lane-mile} & & \text{(range)} & & & & \text{veh.-sec.} \end{array}$$

$$= 5 \text{ kbauds}$$

However, this is an average. At any one time and place, the value of this demand will be liable to statistical fluctuations. These will not be large. More important, there will be systematic variations from place to place and time to time due to travel patterns. Large numbers of vehicles will wish to make changes from one freeway to another. Lane changes will concentrate for some distance upstream of an intersection with another freeway. Other situations, such as a crowd trying to leave a freeway for the ball park just before the game, will also change the demand for lane changes. We do not have the data or the techniques to estimate such effects now.

There will be occasions when a system fault will block a lane. This would require that all the vehicles in the lane have to leave. The first indication that the relevant lane is entering "Closed-Ahead" mode is a single system message, broadcast to all vehicles as an emergency message. In the actual VI system considered, the effective demand for lane-change bandwidth will not increase sharply. Each vehicle will have to split away from its platoon one at a time. Depending on the decelerations admitted, this will take 5-15 seconds per vehicle, or even longer if whole platoons must decelerate to avoid running into the closed zone. Thus, within the range of the transmitters, there will be at most 35 vehicles/mm, but more likely 15 vehicles/min, trying to change lane. This is little greater than the number trying to do so in normal conditions. This means that with this particular design, a blockage will be followed by delays of some minutes to vehicles caught in the same lane behind it, even if there is no capacity problem. The consequences of this are not relevant here.

If we assume that the design and lane-change protocols are changed so that a) all vehicles caught in this way are proceeding in other lanes within 30 seconds, b) in order for this to happen, half as many vehicles as enter the adjacent lanes also transfer to the next lanes, we get the following equation:

$$\begin{array}{ccccccc} 50 & \times & 12 & \times & 200 & \times & 0.3 & \times & 1.5 & \times & 1/30 \\ \text{bits/} & & \text{messages/} & & \text{vehicles/} & & \text{miles} & & \text{change-ln/} & & \text{times/} \\ \text{message} & & \text{In-change} & & \text{mile} & & \text{(range)} & & \text{vehicle} & & \text{sec.} \end{array}$$

$$= 1.8 \text{ kbauds}$$

This quantity has to be added to the normal value.

Messages denoting extreme urgency are very short: “Everybody in lane X, block Y, behind milepost z, STOP,” for example, needs only 44 bits, and is repeated only in case there was a communication error the first time. If it is repeated three times in 50 ms, that is 0.8 kbauds. However, such messages are time-critical; 0.1 or 0.2 seconds more time spent braking can, make a significant difference to the chance of survival in a high-speed crash. To ensure priority, therefore, a channel could perhaps be reserved for this very rare type of message.

Platoon-level Messages: II System

In the II system, messages are exchanged between vehicle and roadside whenever a maneuver such as joining or leaving a platoon or changing lane is carried out. In the II system considered, much of the information passed by a vehicle to the system during a maneuver is passed via the vehicle position detectors (VPDs), and relatively little direct transmission is needed. A vehicle on the automated lane (AL) will receive one message as it crosses block boundaries (average block length 1 mile). In addition, there will be two such messages each time it changes lane (which will happen, on a multi-lane system, perhaps 10 times in the average 15-mile journey segment on the automated freeway). A further 6 or so messages will be associated with each vehicle’s joining or leaving the system. In general, the message type defines the maneuver to be undertaken. Thus CON for these messages is small: it will often contain the lane number, and perhaps one other field of 8 bits. On average, therefore, the bandwidth required here is as follows:

$$\begin{array}{cccccc}
 44 & \times & 47 & \times & 1/15 & \times & 200 & \times & 12 & \times & 1/(60 \times 15) \\
 \text{bits/} & & \text{messages/} & & \text{trips/} & & \text{vehicles/} & & \text{lanes} & & \text{times/} \\
 \text{message} & & \text{vehicle-trip} & & \text{block} & & \text{lane} & & & & \text{sec.}
 \end{array}$$

$$= 0.4 \text{ kbaud}$$

Once again, this is an average. There will be random variations and systematic variations associated with variations in travel patterns.

Emergency messages, and a few slightly less urgent system messages, may need to have a reserved channel so that there are no delays when they arise. The bandwidth requirements are small. The earlier estimate of 0.8 kbauds applies here also.

However, if the emergency is less drastic, there is a need to instruct each affected vehicle individually. As in the VI case, the most demanding fault condition occurs if a fault makes it necessary to divert all the traffic on one lane. The traffic is not in danger, but an excessive delay will mean that more vehicles than necessary must stop and wait. Vehicles need to be told to reduce speed and prepare to exit the lane within about 1 second of the

Table 1. Required Transmission Rates

	kbauds	
	VI	II
<i>Control Data (Regulatory Level) Transmissions.</i>		
Raw requirement	1200	6000
Low power: reduced INTs	10	200
Leader's data by infra-red	0	*
As above + low power & reduced INTs	0	60 } Extra
As above + directional transmission	1	1.5 } Cost
<i>Platoon-level Transmissions.</i>		
A. System messages from gates	0.06	n.a.
B. Maneuver messages:		
average values	12	1
lane closure	14	12
<i>Emergency Transmissions</i>	0.8	0.8

* Not possible.

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incident. Within 10 seconds thereafter, they need to be told what has happened, and it will also be necessary to adjust speed and trajectory of the vehicles in the four (say) adjacent lanes to make room for vehicles leaving the blocked lane. This may need two messages to each vehicle:

The first of these requires, say,

$$50 \text{ bits/message} \times 1 \text{ messages/vehicle} \times 200 \text{ vehicles} \times 1 \text{ times/sec.} = 10 \text{ kbauds}$$

The second requirement is:

$$60 \text{ bits/message} \times 2 \text{ messages/vehicle} \times 200 \text{ vehicles/lane} \times 5 \text{ lanes} \times 0.1 \text{ times/sec.} = 12 \text{ kbauds}$$

These two demands are consecutive and should not be added.

Conclusions

This work was carried out in response to an immediate demand to produce some numbers relevant to AI-IS systems at a national meeting at which views on frequency allocations would be formulated. The two systems considered had already been worked up for a different reason and acted as a base for calculation that was realistic.

Although the two systems discussed here are very different, their communication rates are similar. Indeed, the differences found here are probably smaller than the variations that would arise if we had selected different, but equally plausible, values for the parameters.

The work here has considered only two system designs. However, it appears that the detailed features of these have rarely been used in our calculations. Variations could affect the precise types, number, and lengths of transmissions, but by less than an order of magnitude. It is possible that there are systems in which there is an intermediate amount of intelligence in both road and vehicles in which the requirement for bandwidth is more, or less, than that found here. The remarkable correspondence between the conclusions for these two very different systems may raise the hope that these conclusions can be more generally applied. Further work would be needed to validate such a hope.

Provisionally, we may conclude:

If only the simplest radio-frequency transmission technology is employed, the bandwidth requirements are large and not practical.

The use of infra-red or other non-radio-frequency technology for intra-platoon transmissions eliminates this problem completely in VI systems, and can have a significant effect in II systems. However, it is more costly, because in each case both radio-frequency and infra-red equipment is required. In the II system, some other vehicle data has to be transmitted to the road for safety reasons. **Infra-red** is not satisfactory here, since mud (etc.) will make the **infra-red** roadside equipment inoperable. In the VI system, radio-frequency communication is needed for inter-platoon messages.

In each case, a technology exists which, if practical, can reduce this demand, so that it no longer determines the bandwidth requirement. In the II case, directionality in the transmissions is required. If there are 12 lanes served from the center, and reliance is placed on directionality alone, a beam angle of 10 degrees is required. If there are only four lanes, or if several roadside communicators are used to cover four lanes each, a 40 degree beam is acceptable. In the VI case, the basic technology required is to make the transmission power depend on the message destination. For intra-platoon messages low power is used. With some added directionality, a minimal bandwidth is all that is needed.

The largest transmission rate arises in fault conditions, when it is necessary to carry out some massive set of maneuvers, such as diverting all the traffic in a lane to others

because of a blockage in one lane. This must be added to the normal demand for lane changing and other maneuvers. The rate at which such operations can be carried out may be limited by other features of system design, or simply by the impossibility of diverting a whole lane of traffic into other lanes already operating near capacity. The magnitude of the acceptable delay in these cases is also relevant. Consequently, more work is needed to determine just what is wanted here. However, for both the VI and II systems considered here, a transmission rate of 10-15 kbauds is adequate.

Emergency messages need, perhaps, transmission rates of around 1 kbaud. They are rare. A channel reserved for such transmissions would be idle over 99 percent of the time. However, because the delay in acting on some of these messages can critically affect the severity of casualties, it could be wise to reserve a channel.

All these conclusions refer to transmission rates. The need to ensure that garbled messages are re-transmitted until understood increases the transmission rate. This topic, which is related to the choice of transmission protocol, is not discussed here. To the accuracy that can be achieved using such broad considerations as are employed here, the conclusions of this paper may be unaffected. But the effect ought not to be overlooked in more detailed work.

In order to translate the transmission rates into practical demands for allocations of bandwidth, it will be necessary to investigate and define both the transmission protocols and the extent of re-use of frequencies.

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The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California. The report does not constitute a standard, specification, or regulation.

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