Delay Factors Modelling for Real-Time Traffic Information Systems

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Abstract—The paper is presenting an overview of the factors that lead to critical delays which may occur in multi-modal realtime traffic and travel information systems (MRTTI) employing cellular data network communications. The analysis is taking into account MRTTI systems that use mobile devices to detect position and speed of a vehicle and receive traffic information furthermore used to adjust a previously defined route from origin to destination points. Information transmission delays are also investigated for route guidance systems used in critical applications, such as emergency vehicles management. The identification of the delay factors and some models regarding the delays are presented along with measurements on a real system.

Keywords — real-time traffic information, information propagation delay, jitter

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1. Introduction

The systems used for on-board navigation are well known for their advantages and quite widely spread in road traffic amongst drivers. However, the large majority of such devices are simply GPS-navigation devices with no possibility to use real-time traffic triggered information. The number of such devices that employ traffic and incident actuation in order to adjust a route from an origin O to a destination D is still limited and relying on the coverage area of the system used for communication and to the existence of a traffic management system, used as primary information source. If a RDS-TMC[1] system is used, then the communication is a simplex-type and information is flowing only from the RDS-TMC centre to the mobile device. In more sophisticated systems such as multi-modal real-time traffic and travel information systems, the mobile device detects the user's position and computes a route to a chosen destination based on information requested to a central computer. This information may contain data regarding the actual status of a specific location (e.g., a parking place), along with traffic restrictions or route obstructions on the route to that destination, collected via several traffic and public transport management systems, or parking systems. Emergency vehicles routing to traffic incident is also relying on actuated information regarding current vehicle position and traffic ahead. In some situations, receiving correct information in due time may become critical, especially when such an emergency vehicle also needs traffic signals actuation and prioritization. The paper identifies the main factors causing delay in this information chain and tries to investigate some appropriate mathematical models for evaluating them.

[1] RDS-TMC – a simplex system used for delivering traffic information to onboard navigation devices (Radio Data System – Traffic Message Channel)

The paper is structured in the following parts:

Chapter II is dedicated to the description of the multi-modal real-time traffic and travel route guidance systems architecture and identification of the main delay factors in the information transmission chain. Chapter III is proposing some mathematical models for the main delay factors (with a focus on multimodal route guidance and emergency vehicles navigation systems). Chapter IV performs a brief analysis on the central layer time-shifting, taking into account the numerous processes it has to perform. Chapter V is considering some tests performed on a real system [5] and presents diagrams with recorded delays in information delivery times and table with thresholds accepted for multimodal route computing and information delivery. Finally, chapter VI offers some conclusions and possible future actions to improve the response time of MRTTI systems.

2. Identification of Delay Factors in Mrtti Architectures

2.1 Information Flowing in Complex Mrtti Route Guidance Systems

A complex MRTTI route guidance system is composed of several layers, each of those contributing to the global response time. The main elements of such a system are presented in figure 1. In such systems, the information is firstly analyzed locally in the mobile device and then additional data is requested from the central layer (the MRTTI centre). The cellular network introduces the delay stage D4. When a request from a mobile device is received, the central computer searches for actuated information for the interest zone. If such information is not available or is outdated, then it formulates its own request to information providers (transferring information induces delays in layers D2 and D1).

The central element of this architecture is composed by the MRTTI management centre, where information is collected from various sources and processed (format adaptation, map routing, additional information adding etc.). This layer introduces a typical delay noted as D3. When the information in appropriated format of data is completed, the central computer re-sends actuated information to the mobile device.

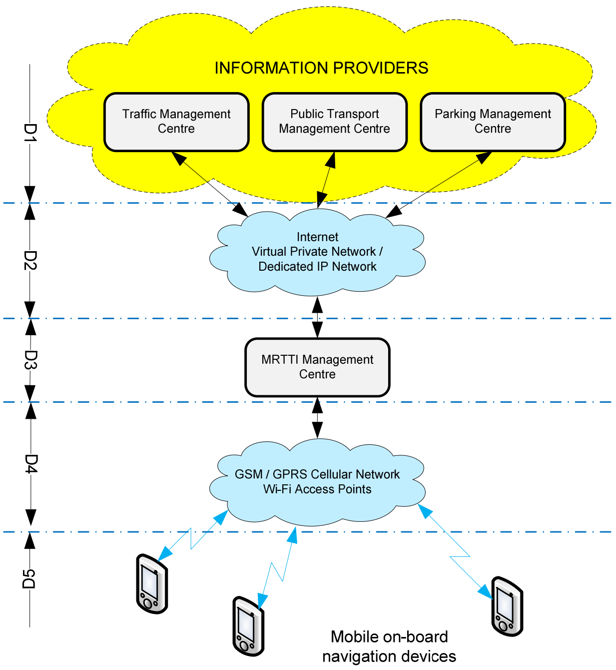

Fig. 1. The layers and main delays introduced by MRTTI navigation systems architecture

It can be observed that in some cases, when a request of information is issued by a mobile device, some of the presented layers have a double contribution at the global time-shifting recorded at the final user.

2.2 Information Flowing in Incident/Traffic Actuated Route Guidance Systems for Emergency Services

Unlike the above presented MRTTI systems, in an emergency traffic actuated route guidance system, the information is only flowing from the dispatcher computer (or operator) to the mobile on-board navigation device. The only information a mobile device sends is the position (and/or other on-board parameters, e.g., identity tag, speed or heading, fuel level etc.). Therefore, the delays that may induce errors in navigation calculations are only produced on the chain from the dispatcher to the mobile device, i.e. communication delays. Figure 2 presents these aspects of the analysis.

Layers 1 and 2 contribute less than in the previous case to the information delaying; due to the fact that related data is permanently resident in the system (such systems have priority compared to civil appliances, and in some cases they originate in the network the information regarding an incident[2]). The most significant part of the time shifting is identified to be produced by the communication system and central data processing. If the emergency route guidance is linked with a traffic actuated controller, then the message has to arrive at the vehicle *before* the vehicle reaches the next traffic light.

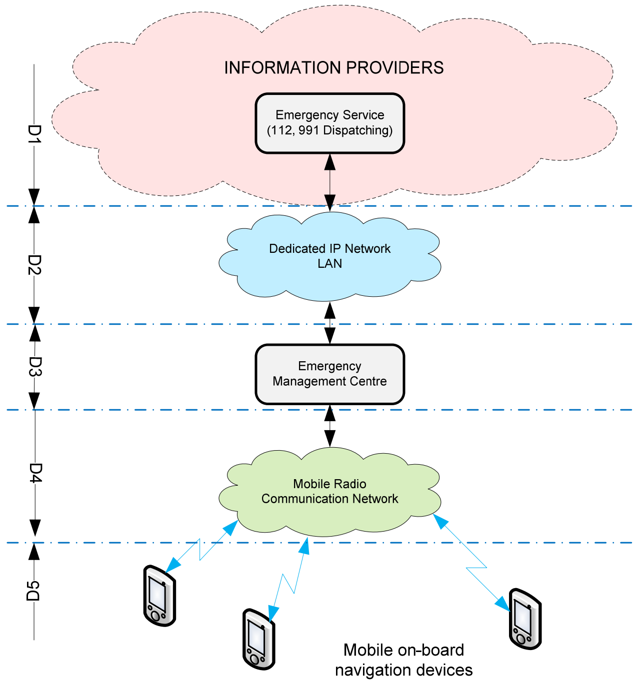

Fig. 2. The layers and main delays introduced in emergency services route guidance systems

The process of route guidance in this case is simpler, because the critical information only flows from the dispatcher to the emergency vehicle, thus offering shorter information delivery delays.

3. Modeling Delays in Information Transmission Chain

3.1 Analysis of Delays in Real-time Multimodal Systems

As stated before, the MRTTI systems employ a double-communication for each route and information-related request. Therefore, in the analysis of time shifting, several stages have to be considered twice in the calculation of the global delay. The most significant delays are introduced as following:

- In the simple routing case, the local processing (D5, figure 1) – the mobile device uses its own sensors (usually satellite navigation sensing, such as GPS) to detect position. Let's denote this delay τ_{lp}. This includes (1): position detection delay θ_d (with presumed GPS hot-start timing), local information processing delay θ_p and route computing time θ_{rc}

$$\tau_{lp} = \theta_d + \theta_p + \theta_{rc} \quad (1).$$

- In a multi-modal routing case, the local processing (D5, figure 1) includes a multi-modal route computing, which induces a different θ_{rc}, larger than the previous one, due to the fact that the processor has to compute several (multi-mode) routes from the actual position

[2] The *e-Call* systems employ incident-triggered message sending via cellular network

(origin) to a selected destination. This selected destination may be inferred from a request to the central computer (for example, when selecting public transport, a person would like to know where is located the public transport vehicle stop, or when requesting for the nearest parking place – the mobile device asks for this information the central computer). Let us denote in this case θ_{rc}^{m} the route computing time for multimodal route guidance and θ_{p}^{m} the local processing time (other than route calculation) in multi-mode transport routing. It is obvious that

$$\theta_{rc}^{m} \geq \theta_{rc} \text{ and } \theta_{p}^{m} \geq \theta_{p} \quad (2)$$

$$\tau_{lp}^{m} = \theta_{d} + \theta_{p}^{m} + \theta_{rc}^{m} \quad (3)$$

where τ_{lp}^{m} is the local processing delay in layer D5, in the case of a multi-modal traffic information system.

- The next stage where time shifting occurs is the mobile (cellular) communication network. Delays (D4 in figure 1) in information transmission, in this case, are dependent on the density of users and availability of modern generation installations (e.g., 4G - LTE[3]) equipment. The necessary time for the information to pass over the communication network is in the first case

$$\tau_{mc} = \xi_{u}(\theta_{r} + \nu) + \xi_{d}(\theta_{a} + \nu) \quad (4)$$

where τ_{mc} denotes the time shifting introduced by the mobile network, θ_{r} and θ_{a} are delays in the network on the up-link (request of information) and down-link (answer) paths, ξ_{u} and ξ_{d} represent random delay factors on the up-link and respectively on the down-link transmission paths, depending on the network coverage and accessibility in difficult reception areas (such as tunnels). Usually, ξ_{u} and ξ_{d} induce severe delays when the signal is lost (ranging from tens of seconds to minutes). The influence of the number of local users is represented in equation (4) by the random network congestion factor ν. For estimating the factor ν, in previous works [7] a model was represented by an adaptation of the Pollaczek-Khinchin formula, where the queuing delay becomes

$$\delta = \bar{\theta}_{s} + \frac{\lambda^{2} \cdot \bar{\theta}_{s}^{\,2}}{2(1 - \lambda \cdot \bar{\theta}_{s})} \quad (5).$$

In equation (5), δ stands for data packet delay at queuing, $\bar{\theta}_{s}$ represents the average service time at first transmission, $\bar{\theta}_{s}^{\,2}$ the average service time at second transmission (retransmission) and λ the arrival rate of messages at the queue. Considering a coefficient for the congestion of the network due to multiple simultaneous transmission requests, we can further develop the model such as

$$\nu = \frac{\delta}{\eta} = \frac{\bar{\theta}_{s} + \frac{\lambda^{2} \cdot \bar{\theta}_{s}^{\,2}}{2(1 - \lambda \cdot \bar{\theta}_{s})}}{\eta} \quad (6)$$

where $\eta \in (0.8 \div 0.95)$ is a random coefficient directly dependant on the number of instant cell users and $\bar{\tau}_{s}$ is a geometrically distributed random variable. The service time is proportional to the number of the transmission attempts and inversely with the cluster (data packet) size. The coefficient η is containing this information.

- Relevant MRTTI data and electronic-format maps[4] transmission through Internet Protocol require consistent, non-restrictive network bandwidth as well as the navigation computer hardware sufficient to support not only the communications of the agent but also other tasks being performed on the navigation computer. Delays can occur in at least two ways:
  - *Delays due to propagation, θ_{pr}*. This type of time shifting is related to the distance that IP packets must travel through the network, the number of hops that packets take through a network, the available bandwidth of that network, and other network traffic.
  - *Delays due to encryption and messages processing, θ_{enc}*. VPNs encrypt data in order to ensure privacy over an otherwise public network. Encryption of packet data takes time and can increase delay in a network. The VPN should be implemented with hardware acceleration in order to minimize delay. If a PC is used as one of the endpoints in a VPN connection, the PC may introduce a large delay in processing the encryption/decryption algorithm.

  However, when transiting a VPN network, the total time a data packet is taking from source to destination (end-to-end delay) is composed of *i) the processing delay, ii) the queuing delay, iii) the serialization* delay and *iv) the propagation delay.* The total delay τ_{ic} produced by the VPN communication is modelled with

$$\tau_{ic} = 2\xi_{IP}(\theta_{pr} + \theta_{enc}) + \xi_{J}\theta_{j} \quad (7)$$

  where ξ_{IP} denotes a random coefficient depending on network load, ξ_{J} a random coefficient depending on the variation of the delay (also called *jitter*[5]) and θ_{j} the average variation of delay on a defined period of time.

- Delays produced by the third-party information providers. In MRTTI systems usually the information related to traffic congestions or events on a route is collected via third-party systems, such as (figure 1) traffic management systems. Except the time shifting produced solely by the third-party system operation, there are some delays that may also be modelled i.e. conversions of different data formats (presented as D1

[3] 4G-LTE – fourth generation of GSM data transmission technology – Long Term Evolution, that allows for rapid transfer rates

[4] Delays due to processing operations for formatting of maps, such as WFS (Web Feature Service) or WMS (Web Map Service)

[5] The jitter represents an undesired deviation from true periodicity of an assumed periodic process (or signal, in electronics or telecommunications)

in figure 1). Usually, this process is carried on by a so-called Commonly Agreed Interface, or CAI. Let us denote these delays with τ_{CAI}.

Concluding and considering (1), (3), (4) and (7), the total end-to-end delay in simple route guidance systems (using RDS-TMC) may be written as

$$\tau_{RDS} = \tau_{LP} + \tau_c \tag{8}$$

with τ_c being the RDS-TMC channel communication delay.

For MRTTI systems the total end-to-end delay on the information chain becomes:

$$\tau_{MRTTI} = \tau_{lp}^m + \tau_{mc} + \tau_{ic} + \tau_{CAI} \tag{9}.$$

3.2 Packet Delaying in IP Networks and VPN Networks

In order for a MRTTI system to offer good service and with a suitable security, VPN networks, equipped with QoS[6] are to be employed in its architecture [1], [2]. VPN networks that are suitable for such applications may be those enabling QoS also suitable for providing business-class voice along with video support that meet the following requirements [2]:

- end-to-end delay $\tau_{ic} < 150$ ms
- end-to-end *jitter* $\theta_j < 50$ ms
- end-to-end packet loss less than 1 percent.

The usual predictor used for modeling end-to-end delays in current TCP[7] networks is based on Jacobson's [4] algorithm, where a TCP sender records a "round trip time (RTT)" when it receives a correct acknowledgement packet. Considering $\tau_{IC}(n)$ the observation for the nth packet, we obtain a recursive model for τ_{IC}:

$$\overline{\tau_{IC}}(n+1) = (1-\xi_{IP})\overline{\tau_{IC}}(n) + \xi_{IP}\overline{\tau_{IC}}(n) \tag{10}$$

where ξ_{IP} has recommended values around 1/8.

4. Analysis of the Central Layer Time-shifting

The central layer (MRTTI dispatcher) has a substantial contribution – denoted as D3 – on the overall time-shifting produced by the system. In fact, if we consider a correct service response from layer 1 (Information Providers, D1), then the most important delay is produced by D3. This is due to the fact the CAI and the Regional Data Service Server (RDSS) have to convert, process, re-convert and set ready for broadcasting information in different formats (such as maps presentation to final user). Another option is that the RDSS not only provides dynamic traffic information as standalone data, but also generates dynamic vehicle routing itself by means of provision of waypoints for navigation to the traffic information service providers (figure 3). The most time-consuming service from the whole palette of services offered by the MRTTI system is, according to field measurements, the *Dynamic Traffic Information Service (DTI).* This service has to acquire real-time traffic information, to convert it regularly into appropriate formats and to constantly update relevant data to users that travel on a route that involves that information.

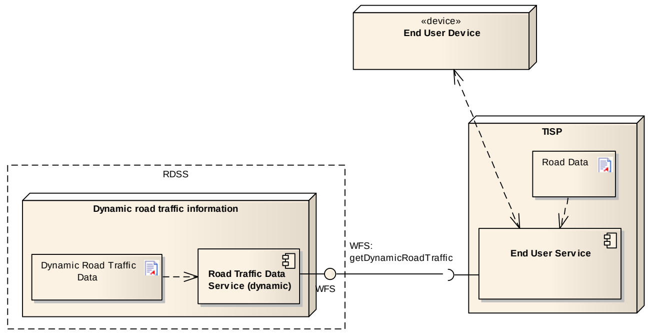

Fig. 3. The service chain that produces the most significant time-shifting in data processing – in the central RDSS core

It is difficult to obtain a very close mathematical model of the overall time-shifting produced by this segment D3, due to the fact the service itself has a high complexity [5]. Figure 4 shows the use case diagram for the main operations produced in this layer D3.

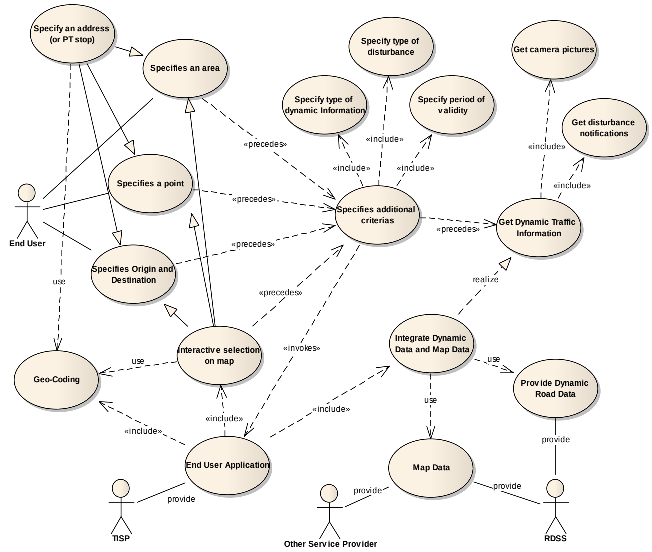

Fig. 4. Use-case diagram showing operations that produce consistent time-shifting for the core service Dynamic Traffic Information

In figure 4 it should be considered only the main operations timings, in order to obtain a simple model of the process. The following is an application for the core service DTI, which only considers time-shifting for the main operations produced in RDSS:

- Time necessary for local selections of the user (θ_{OSU}). This includes operations like: method for declaring origin and destination of trip and specification of additional criteria;
- Time shifting produced by importing dynamic traffic information (θ_{DTI}) - this is an operation with a high

[6] QoS – Quality of Service, a concept for IP networks that manages the following elements: bandwidth (the amount of data that can be transmitted at once), delay (time to send data from source to destination), jitter (variation in delay) and reliability (packet losses).

[7] TCP – Transfer Control Protocol

degree of incertitude, in terms of duration. It depends on the availability of data and correct operation of third-party information providers;

- Time shifting produced by the end-user application operations, also including a certain degree of jitter, θ_{EUA} - it includes integration of dynamic and map data on the electronic map [8]. This stage is difficult to compute due to the large number of possible solutions (mixed routes) – the response time will require more time than those for non-intermodal services.

- A random component, depending on the hardware configuration and mobile operating system employed by the user mobile equipment, ξ_{UE}.

Because θ_{OSU} is not a part of the model (it is a time shifting produced by the user himself in choosing different criteria for his/hers route and transport mode selections, it will be ignored in the estimation of this sub-model. The following estimative sub-model (11) for the layer L3 time-shifting is proposed:

$$\tau_{CAI} = \xi_{UE}(log_R l + log_N l) \cdot \theta_{EUA} + \theta_{DTI} \qquad (11)$$

where l represents the length of the route (in km), R denotes the number of alternative routes to compute and N the number of transport modes used in multi-modal public transport route alternative.

5. Testing the Models and the Real System

The RTTI system [6] has been implemented in six European cities and several tests have been performed, including performance testing. Since in such a system the focus in on the final user, the performance has to be tested over the full information chain, which is from the handheld to the backend system (with the different processing steps distinguished in this paper). However, because there are third party actors involved in this chain, the tests should only refer to the components that really belong on the own system's information chain, that is the CAI and RDSS.

5.1 Test I

The purpose was to analyze the performance of the system on the CAI-RDSS-end user chain. The test has been performed for a number of 15 requests of public transport routes on a distance of 8.6 km in Vienna. The response times were biased as in figure 5.

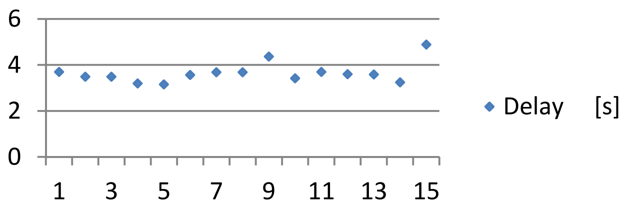

Fig. 5. Delay of response recorded on a set of 15 tests performed for a 8.6 km route (Vienna, public transport). Horizontal axis: number of test, vertical axis: delay [s]. Maximum jitter: 1.04 s

5.2 Test 2:

A set of 15 requests for route with public transport, Vienna, route length: 18.3 km. It appears that in this case, the jitter recorded is much more significant: 1.85 s.

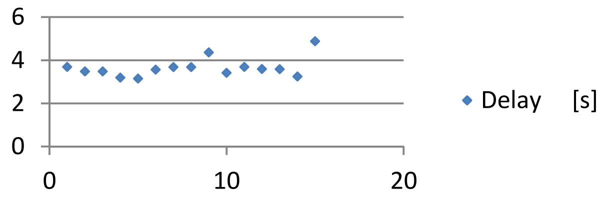

Fig. 6. Delay of response recorded on a set of 15 tests performed for a 18.3 km route (Vienna, public transport). Horizontal axis: number of test, vertical axis: delay [s]. Maximum jitter: 1.85 s

5.3 Simulated: τ_{CAI}

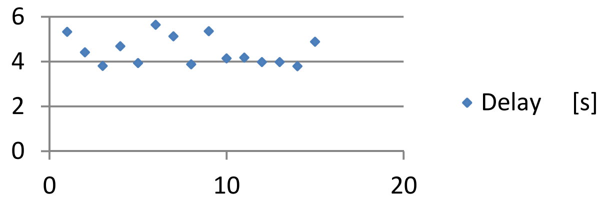

Fig. 7. Simulation for τ_{CAI}. Horizontal axis: number of event; vertical axis: τ_{CAI} value in seconds

A simulation to determine the variation of τ_{CAI} has also been performed (figure 7), considering the following values: maximum jitter: 3.69 s; $\xi_{UE} \in (0.06 \div 0.17)$, $N \in (2 \div 4)$, $R \in (2 \div 5)$, $N, R \in \mathfrak{R}$. A comparison has been made with the tests performed on the most complex service (request of multi-modal route from origin O to destination D), approximately the same length as in Test #2. The results are shown in Table I.

TABLE I. THRESOLDS FOR MULTIMODAL ROUTE REQUEST [5]

Testing period [s]	Number of request sent in time frame	Average maximum threshold for response time for each request [s]	Notes
1	1	3,8	
1	2	4	
1	5	5	
2	5	4	Average distribution allows for lower maximum peaks thus lower average response time
2	10	4,8	Average distribution allows for lower maximum peaks thus lower average response time
5	20	4,5	Average distribution allows for lower maximum peaks thus lower average response time
5	50	5	Average distribution allows for lower maximum peaks thus lower average response time

6. Conclusions

In this paper, an analysis on the effects of multiple stages processing in MRTTI systems has been performed. The multi-modal real-time traffic and travel information systems have been split in different layers and effects in terms of information delaying have been analyzed. Because such systems are very complex and, in fact, they are composed of several sub-systems, modeling the time-shifting of information messages due to signals processing in the different functional components is a difficult task. In some stages, the information is delayed because of the lack of quick response of third-party subsystems, or communication networks. The authors have tried to identify the different effects of each layer, providing a mathematical model for the delay, where possible or appropriate. Considering the results of a research project [5], and the effective participation at the quality tests performed for the system implemented in Europe, some basic conclusions can be drawn:

- The MRTTI applications used for emergency vehicles routing must have a closely controlled time response, in order to give an appropriate help in vehicle route guidance and quick response for traffic signals actuation.
- It is extremely difficult, even impossible to create a model for the response of third-party systems that are used for collecting traffic/route information – this depends on too many factors: technologies employed, architectures of the systems, interfaces, prioritization of messages etc.; these third-party systems have the most significant influence in the variation (jitter) of response times.
- The delays produced in Internet/VPN data communications can be mathematically modeled and have a less influence in delaying of traffic information messages, compared to the previous case. The delays usually range in the domain of seconds, if a correct QoS is ensured for the network [2], [4]. This time-shifting does not usually affect a normal, civil on-board route guidance appliance effect on navigation.
- The delays produced by the mobile communication network, if GPRS, give also the possibility to create a mathematical model, and their amplitude is significant only if the network is too congested or if there are losses of GSM signal strength below a certain level. Compared to the MRTTI process speed, these delays are still in the acceptable domain of values.
- It resulted from the tests that processing of data in the mobile device is delaying information delivery time because of: poor hardware processing power, low memory or graphics hardware. Also, the operating system has its contribution to the processing time. Regarding position sensing, the mobile device has to be in a good GPS signal coverage in order to collect rapidly geographical position, otherwise routes calculation from the actual position becomes longer.
- Longer routes computation creates longer response times, which also increase in case of public transport mode selection (the device has to multiply its calculations for several routes, employing several transport modes). Variations in response time also increase in this case and range usually in the order of seconds.

Future actions: the authors consider that information systems in traffic will become more and more necessary, taking into account the continuous increase in road traffic density. With the support of growing capacities and quality of service that the communication networks ensure, such systems will become part of the next-generation road vehicles, making driving safer and less stressing. New standards, related to intelligent transportation systems are going to be developed at the European level, also including specifications for MRTTI systems. Research in this area, combined with ad-hoc short range dedicated vehicular communications have a great potential to improve present road traffic safety and environmental protection.

Acknowledgment

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