Evaluation of in-vehicle decision support system for emergency evacuation

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Abstract
One of the most important issues in Decision Support Systems (DSS) technology is in ensuring their effectiveness and efficiency for future implementations and use. DSS is prominent tool in disaster information system, which allows the authority to provide life safety information directly to the mobile devices of anyone physically located in the evacuation area. After that a personal DSS guides users to a safe point. Due to the large uncertainty in initial conditions and assumptions on underlying process the implementation and evaluation of such DSS are extremely hard, particularly in real environment. We propose a simulation methodology for the evaluation of in-vehicle DSS for emergency evacuation based on transport system and human decision-making modeling.

Keywords: Decision support systems, emergency evacuation, evaluation, transport simulation

1 Introduction

The design and implementation of a DSS comprises computer technologies, information processing, organizational structure and human behavior. Conjointly, it prevent the creation of unified rigorous and precise scientific methods for the evaluation of DSS which aim to assess whether the user needs are properly met, the system is suitable for tasks, and users perform better with the new system (Kirakowski & Corbett, 1990). Now DSS have became a very important aspect in all types of jobs and everybody’s lives there is a need to have more rigorous methods to the evaluation of DSS based on objective (quantifiable) criteria. In accordance with (Rhee & Rao, 2008) the sequential approach to DSS evaluation categorizes evaluation process into three components: identification of evaluation criteria, formative evaluation, and summative evaluation. Evaluation criteria (or metrics) are a basis for evaluation. It refers to an objective list that defines the usefulness of a system. A formative evaluation is an iterative process of weak points elimination until the desired objectives are reached. A summative evaluation is a final stage in this process that attempts to determine the system efficacy. It should be noted that in this paper the evaluation of DSS is viewed from a standpoint of both the
efficiency and the effectiveness. Efficiency for a DSS is measured as the speed of decisions or the cost of the decision-making process and considered as system-oriented assessment. In contrast, effectiveness is concerned with beneficial to the end user. Taking into account this distinction, it is clear that evaluation should be done in different manner, as the relevant criteria are usually quite different. Consequently, a comprehensive DSS evaluation methodology must address both effectiveness and efficiency (Evans & Riha, 1989).

The most natural way for the evaluation of DSS is to measure its effectiveness and efficiency using experimental methods (empirical evaluation). But Kuwata (Kuwata, Noda, Ohta, Ito, Shinhoda, & Matsuno, 2002, August) noted that disaster DSS (like emergency evacuation) is a specific type of DSSs. They differ from usual DSSs because they require real-time responses and performance, more-efficient user interfaces and are difficult to evaluate in a realistic environment. Furthermore, emergency response DSS require considerable efficient evaluation because of their importance (Evans & Riha, 1989). This can be done through simulation approach when both environment and decision-making process are implemented with the mutual influence. An evaluation framework for this purpose is proposed. A case study will be used which demonstrates the evaluation of the effectiveness and efficiency of an in-vehicle DSS for emergency evacuation.

### 2 Related works

A growing threat of natural and technical disasters is compounded by the concentration of populations into big cities, placing more people at risk. Main problem with large scale emergency evacuations is that the population is growing faster than the development of infrastructure (road capacity). As a result, potential evacuation is getting more difficult and mitigation strategies should be studied. Normally emergency management planning is performed by special agencies but the role of road services (including information) is getting higher. Usually transportation research on emergency situations is focused on better coordination between different agencies in relation to large scale evacuations (Alsnih & Stopher, 2004). The main issue is avoiding of congestion collapse on the routes with limited capacity by centralized management. The common feature of modern emergency DSS is a microscopic model with dynamic traffic assignment (routing). The history of micro traffic simulation has started in 1990s. The rapid development of this class of models supported by the growth of computing power led to a large number of software packages with similar functionality. But as mentioned in (Alsnih & Stopher, 2004) for some reasons they are not useful for emergency evacuation modeling. In last two decades several DSS for transport planning based on micro traffic simulation in ordinary conditions have been implemented. Some of them have been adapted to simulate transportation systems in emergency conditions in order to support evacuation planning and/or operative stages (Vitetta, Musolino, & Marciano, 2009). The key problem in evacuation management is a routing for reducing evacuation time. In ordinary conditions the problem of vehicle routing is well studied. For example in (Tarantilis & Kiranoudis, 2002) the solution based on spatial DSS and efficient vehicle routing algorithm is proposed. Many commercial solutions (TomTom, Garmin, Google Maps and others) have the efficient routing algorithms that help the customer to minimize travel time. Information delivery is usually organized through mobile applications with specific tips on choosing the path. In contrast to centralized management, the possible solution is facilitating the self-organized evacuation by in-vehicle DSS, which allows the authority to provide life safety information directly to the mobile devices of anyone physically located in the evacuation area. The major drawback of this approach on existing infrastructure is that it is focused on beneficial to the particular user and the system effect of mass use is not taken into account. Theoretically that means that popular solutions for vehicle routing are not very useful for evacuation problem. For evacuation routing in congested urban networks a number of solutions have been proposed. For example, in (Ren, Huang, Cheng, Zhao, & Zhang, 2013) an evacuation routing algorithm is combined with signal
optimization model. A lane-based evacuation routing algorithm with case study in Salt Lake City is proposed in (Cova & Johnson, 2003). An optimal routing strategy based on Nash equilibrium approach and implementation in popular simulation framework MATSim have been describes in (Lammel & Flotterod, 2009). A more general evacuation planning using multiobjective evolutionary optimization has been studied in (Saadatseresht, Mansourian, & Taleai, 2009). One of the key problems of all proposed solution is an information delivery to end user. Any strategy can fail if end user doesn’t have clear and timely instruction for the emergency behavior.

In this paper we try to investigate the applicability of existing mobile infrastructure to emergency evacuation when no specific emergency algorithms are applied and only a fraction of society follows more reasonable evacuation strategy. Furthermore we want to quantify the system effect and advantage for DSS users.

3 Simulation of Emergency Evacuation with personal decision support system

3.1 Urban models for transportation

Despite the presence of a large number of microsimulation (multi-agent) models even with free source code we decided to implement our dedicated model specifically for the problem being studied. This decision is motivated by the full source code control and flexibility of implementation for the new features. Transportation model is used in two ways, one for the estimation of realistic initial condition for evacuation, and the other for simulation of agents’ movement in emergency situations under specific logic. The input data for the simulations is the transport demand which refers to the amount and type of traveling people. It allows making a dynamic generation of agents with the specific properties and a binding to geographical location and time. Transport demand model involves the following:

- Traffic depends on the hours of a day.
- There are different routes between two specific points.
- Time spending by agents at various points complies with a regular schedule, which can be considered as deterministic.
- Daily activity chains depend on social group.

In general the transportation model is based on a synthetic population, which is a randomly generated set of individuals that is based as much as possible on existing data. In Figure 1 the input data for demand modeling is shown.

Route generation is done on the map which is represented by a road graph. A OpenStreetMap (OSM) was chosen as a main source of GIS data. An additional work for the converting from the OSM format to the new representation of the road graph has been done. OSM data covers both road infrastructure and buildings. The land use is obtained from the population database provided by the Federal Migration Service. All the buildings were divided into two categories: residential and offices (with other type of usage). All the buildings displayed in Figure 1a have the specific color. The color palette shows the number of residents (from green to red). Non-residential buildings are highlighted with grey color. The route is chosen randomly between residential and non-residential buildings for every active agent. The schedule of daily activity is shown in Figure 1b. It is approximated in the form of histogram with 1-hour step and reflects the work timetable for the most of the companies (including offices and commerce). The accuracy of this approximation is not crucial to the evacuation problem because it generates an initial configuration of agents at the time of danger notification which is much more dependent on the current hour than on agents’ time distribution.
For the case study area a Vasilyevsky Island in St. Petersburg (Russia) was chosen. It is bordered by two distributaries of the Neva River in the south and northeast, and by the Gulf of Finland in the west. The area of the island is approximately 11 square kilometers and the population is about 200,000 people. This is a lowest district in St. Petersburg and it is vulnerable to flood risk despite of the active city protection by the barrier (Ivanov, Kosukhin, Kaluzhnaya, & Boukhanovsky, 2012; Krzhizhanovskaya, Melnikova, Chirkin, Ivanov, Boukhanovsky, & Sloot, 2013). This is a very interesting case study for evacuation management as the island has only four exits relatively close to each other (See Figure 1a).

Traffic model is composed of several sub-models which cover different aspects of vehicle movement: departure, movement on an edge, intersection transit, routing. Simulation space in a model is represented by the directed road graph. Each moving agent is attached to a one edge of the graph. When an agent receives the notification it leaves point of residence (some node in the road graph) and starts traveling according to its evacuation route. If the agent can’t enter the edge because of traffic congestion it waits for departure in a queue. Such queues of leaving agents are attached to each node of a road graph.

On the edge of the road graph agents move according to the intelligent driver model (IDM). It is a time-continuous car following model for the simulation of freeway and urban traffic (Treiber, 2000). It describes the dynamics of the positions and velocities of single vehicles on free road, at high approaching rates and at small net distances. IDM has the following parameters: desired velocity, minimum spacing, desired time headway, acceleration and comfortable braking deceleration. Different values of these parameters determine the different categories of drivers. For the traffic simulation the following categories were used: timid driver, normal driver, aggressive driver and trucks.

The model of agents’ movement takes into account intersections transit. Agents decrease speed before the cross. A value of velocity reduction depends on the fact: is the next edge after the cross is busy or not. It means that if there is not enough space at the beginning of the next edge, the agent will stop before the intersection. Otherwise it will only reduce its speed to a value which allows making a turn safely. This technique is implemented for the agents which have no leader according to IDM. For these agents a virtual leader is introduced and represents the intersection ahead.

Both types of agents: with DSS and without DSS, determine their route by minimizing of its estimated travel time. For agents without DSS fastest route is defined as the shortest path to the closest exit. For this purpose Dijkstra algorithm is used. For agents with DSS routing procedure is performed with a certain period (10 minutes of model/real time) in order to find optimal way based on the actual...
information about traffic. For this purpose each agent has its own update timer which starts at agent departure time. Weight of an edge in this case is represented by the average edge transit time. This value is calculated for each edge within a certain time window on the base of the individual agents’ travel times measured for agents who have passed the edge within this time window.

3.2 Decision making and evacuation model

The distinguishing features of traffic simulation in emergency situations can be summarized by the following:

- Every agent follows its pre-calculated route until notification about danger.
- Agents’ population consists of two types of agents: agent with and without DSS which interact with each other in the same environment.
- Notified agent without DSS follows the shortest route to the nearest exit (one of four bridges) and doesn’t change the decision.
- Notified agent with DSS follows the recommendation of the system. The update period is setup to ten minutes. That means that new recommendation can lead to the evacuation through another exit.
- DSS aims to find the fastest route for the user. The fastest route is almost always longer than shortest route because the system tries to avoid the most congested zones.

The shortest and fastest route is calculated by the Dijkstra algorithm. The difference between two cases (with and without DSS) lies in the mode of edge weight assessment. In the first case the weight of the edge is its length. In the second case the weight of the edge is calculated as a mean edge transit time.

In general it is intended to mimic the real situation at the most without unnecessary complications. The architecture of the framework for the simulation of the evacuation process is shown in Figure 2.

![Figure 2: The architecture of the framework for the evacuation process simulation](image)

Grey blocs in the Figure represent the input or output data. White blocks with rounded corners represent computational modules. Simulation of evacuation process is a part of agent-based traffic simulation module that is supplemented by the special logic for agents with and without DSS. Here the individual properties of agents are the categories of drivers that play no role in demand modeling.
Simulation of evacuation process can be started from any desired moment, but the most interesting result is expected when the number of agents is close to the maximum.

Model assumptions which are not always true:

- Every agent always follows the chosen route (as with as without DSS) and never makes wrong turns or change its decision under certain circumstances (for example, one can see free road).
- An agent without DSS always knows the nearest exit. In reality in some locations it is hard to estimate the nearest exit even with a map.
- The difference between different DSS with optimal route calculation is neglected.
- An in-vehicle mobile device always keeps connection with the server.

The behavior of agents is quite complicated. Thus the basic verification method is a dynamic visualization of agents’ movement and additional cumulative statistics. Figure 3 (a,b) depicts two examples of simulation visualization (screenshots). Underlying map is downloaded from the OpenStreetMap server as graphic tiles. The visualization module supports different layers reflecting the most relevant information for real-time observations. For example, the most congested roads are highlighted with the red blocks of different size.

![Figure 3: Visualization of simulation process (a,b), notification function (c) and cumulative diagram of bridge use (d)](image-url)

The notification of agents is not instant and it is distributed in time (see Figure 3c). This function is chosen according to the studies of Lewis (Lewis, 1985).
Each agent is depicted as a dot whose color indicates the desired exit. This enables to track changes of the agent decision to use different exits over time. Form of representation on a black background (see Figure 3b) gives the clearest view of this kind of changes. In-vehicle DSS has a certain update period and for some experiments with a high proportion of DSS-users it shows dramatic changes in agents’ behavior over time. All the experiments were carried out with the five-minute update period for each DSS (not for all at the same time). The change of decisions leads to periodic fluctuations in the number of agents (see Figure 3d) moving through given exit (bridge). Moreover these fluctuations make the evacuation process quite unbalanced at given moment and thus throughput of bridges is not used at full capacity.

There is an option of running the simulation in batch mode without visualization in order to get better performance. Actual simulation time mostly depends on the number of agents. The ratio of model time to the real time ranges between 5 (nobody uses DSS) and 10 (everybody uses DSS) on Xeon E5-2650 (2GHz).

4 Evaluation metrics

Evaluation metrics of DSS for emergency evacuation is closely related to overall process of evacuation efficiency. According to (Alsnih & Stopher, 2004) emergency situation analysis usually involves the following: the specification of disaster scenarios, definition of evacuation transport zones, the determination of the size of the evacuation population, updating traffic conditions, simulating changes in the roads resulting from extreme events, identifying heavily used roads, centralized or decentralized evacuation management, calculating clearance times for each scenario. In our study we do not determine the specific cause of the evacuation and complete evacuation is supposed. Thus we do not simulate closed roads resulting from extreme events, although technically our framework has the feature of water propagation simulation resulting from flooding. Traffic is considered known for the DSS server as nowadays the number of DSS users combined with other data sources (cameras, sensors etc) gives sufficiently accurate traffic information. All the exits from the island are considered equivalent and none of them is considered to be preferable. Thus the expected improvement of traffic is related to the more balanced evacuation through all the exits. We do not introduce any centralized management of the evacuation process as it is difficult for quantification and the most interesting is the study of the self-organization process that will take place anyway. Thus the efficiency for a DSS, i.e. system effect of its mass use, is considered as the reduction of total evacuation time when a certain fraction of people uses DSS compared to a scenario where no one uses DSS. Effectiveness is considered as the reduction of evacuation time for a particular DSS user compared to evacuation time of agents that do not use it and follow the simple logic of the nearest exit.

5 Simulation result

Various simulation scenarios are determined by the different numbers of DSS users. Step of change is set at 5% with the range of DSS users’ percent from 0 to 100. Evacuation start time is the same for all the computational experiments and is set at 6 pm. The number of agents is chosen at 12500, 25000 and 50000. Evacuation time is the difference between the notification started and the moment when the last agent left the island. During the computational experiment we trace the following values for each agent: evacuation time, the desired exit and each case of decision change (for DSS users), an expected and actual length of the route. In addition, we trace the number of agents passing through each exit (bridge) every 10 seconds. This allows us to estimate the balance of the use of different bridges. Figure 4 depicts two main indicators of simulation reflecting the system effect:
exit use balance and the total evacuation time for each scenario which is normalized for percentage representation.

Exit use balance is presented as follows. The proportion of agents who were evacuated through each bridge is calculated. The difference between minimum and maximum values is considered as a main indicator of the exit use balance. It is assumed that the better balance results in the least evacuation time (Figure 4b). Actually for 25000 of agents we found that the least evacuation time was reached very close to the first balanced use of exits. But despite the fact that the balance is maintained up to 100% of DSS user the actual evacuation time starts to decrease just after the optimum at 80%. Although the efficiency drop is not very big one can expect the continued growth of efficiency with the increasing number of DSS users. For this case special algorithms are required.

![Figure 4: Simulation result of computational experiments: (a) evaluation of the exit use balance for 25000 of agents, (b) the relative evacuation time for each scenario](image)

One of the interesting findings is that the rate of evacuation time fall is linear from zero percent of DSS users up to the optimum. After that a sharp change in trend is observed and a total evacuation time grows slowly up to saturation. One can assume that a trend change is determined by the DSS logic focused on individual user benefits and system effect when the most efficient route for a single user is not optimal for the entire system. However, at this moment the number of users of navigation systems is far from 50% and existing algorithms may be quite effective for the purpose of evacuation. But with the growing popularity of their use or when autonomous vehicles will become a reality in the future other algorithms that will operate on the concept of transport flow will be needed. For other numbers of agents key findings are roughly the same, yet the optimum tends to a larger percentage of DSS user and overall efficiency of DSS use is growing with the number of agents.

It should be noted that the system optimum is in conflict with individual benefits. One can see in Figure 5 that the greatest personal benefit of the DSS use is achieved with a low percentage (~25%) of its use in the entire population. The relatively big mean evacuation time for DSS users at low percentage can be explained with the effect of very high congestion blocking free exits for all the users. When the effect of “smart” users takes place at 25-35% the mean evacuation time for DSS users tends to minimum.

At 80% of DSS users the efficiency of evacuation is approximately the same for all agents. After that an amazing effect that means evacuation time for DSS users is higher than for users without DSS is observed. This can be explained by the fact that the system directs users to the same paths, and after finding their high loading it changes the route. This can happen often and leads to a very inefficient route of evacuation. At the same time, the evacuation time for agents that do not use DSS decreases continuously up to the maximum percentage of agents using DSS.

The results in Figure 4b and 5a are related to each other with the following equation:
\[
\min(T_{all}) \iff \min(\overline{T}_{DSS} \cdot p + \overline{T}_{noDSS} \cdot (1 - p)),
\]
where \(T_{all}\) – total evacuation time, \(\overline{T}_{DSS}\) – mean evacuation time for DSS users, \(\overline{T}_{noDSS}\) – mean evacuation time for users without DSS, \(p\) – percent of DSS users, "\(\iff\)" – concordance between values. We can see that the optimum is reached at the level of \(p \approx 80\%\) for both datasets.

We found that for some agents at different points in time the route to all four exits has been proposed. However, this has not been reflected explicitly in the mean length of the route. Change in the length of the route does not have explicit and intuitive trend but in all cases the length of the route for DSS users is significantly longer. The mean traveled route length for agents without DSS is the same for all the experiments. This confirms that as opposed to the travel time there is no influence of DSS users on the travel route length of agent without DSS.

6 Discussion

In general, the computational experiments exhibit the logical and interpretable results of simulation and under certain assumptions some conclusions can be made. First of all, the use of the DSS greatly reduces total time of evacuation even without optimal algorithm for centralized flow traffic management rather than for individual users. This can be achieved on existing infrastructure without significant modifications. The second main conclusion is that when an approximately half of DSS users in the total number of agents is reached other routing algorithms are required. Indirect evidence that better time of the evacuation can be achieved is the relatively large imbalance in the use of exist (bridges) for the optimal scenario (system efficiency). It is obvious that the best result is to be achieved with a balanced use of bridges. In addition, we found significant oscillations in the number of evacuees through each bridge in time that shows insufficient effectiveness of their use. We believe that these conclusions remain relevant in certain changes in the input data. Baseline scenario has

![Figure 5: Evaluation of DSS users benefits for 25000 of agents: (a) mean evacuation time, (b) mean actual route length](image)
obvious disadvantages concerning relatively simple logic of agents’ behavior. For example for the most dangerous situations most of agents will try to help their family too. Thus, family links must also be taken into account. In an emergency, many people can behave inadequately that may be a problem for simulation. Moreover, only one geographical region was considered. Some of the conclusions may be inappropriate for the other geographical location. Fortunately our framework can easily be adjusted to any region and this is a part of the future work. Another important research direction is to find the optimal routing algorithm for the case when most people use DSS. Some prominent algorithms were found in existing literature. Last important issue for the research accuracy is the sensitivity of results to the input parameters. For example the impact of microsimulation model parameters on the simulation output is unclear. Some conclusions can be different for other numbers of agents.

Other important issue is a reliability of infrastructure. Our experiments were carried out under the assumption that the mobile network is always available. In reality this may not be true. Moreover the personal routing algorithm works well on existing mobile devices. For the centralized management a routing algorithm with a high probability have to work on the central server of the system serving at the same time a large number of clients. For that a special urgent computing infrastructure is required.

7 Conclusion

This paper has outlined the tasks involved in the evaluation of in-vehicle decision support system for emergency evacuation. On the basis of simulation it was shown that the use of the in-vehicle DSS greatly reduces total time of evacuation as for DSS users as for the rest of agents. The key finding is that the significant effect can be achieved on existing infrastructure without drastic modifications. The overall effectiveness of the evacuation depends on the fraction of DSS users in a total evacuee number. For our case study the best time of evacuation was reached at 80%-85% (12.5 – 50 thousands of agent) of DSS users and it is approximately two times faster than without the use of DSS at all. Before optimum the rate of evacuation time falls linearly. After that, the efficiency of evacuation started to decline and other routing algorithms dealing with traffic flow rather than with individual users are required. A proposed framework has a flexible architecture for the implementation of new features and can easily be adjusted to any region. Future research is related to a more accurate taking into account behavior characteristics in critical situations and the study of geographical structures for more effective evacuation.

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References


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