Estimation of failures probability in alliances of transportation systems

Petr MOOS*, Mirko NOVÁK**, Zdeněk VOTRUBA**, Petr BOUCHNER**
*Department of Informatics and Telecommunications
**Department of Telamatics and Control
Czech Technical University in Prague, Faculty of Transportation Sciences
Prague, Konviktska 20, ZIP 110 00,
Czech Republic

ABSTRACT

In this contribution the problems of transportation systems alliances reliability and safety are discussed, with special regard to their safety and security against the negative impacts caused either by natural traffic circumstances or by accidental situations. Four approaches to the task of improving the operation reliability and safety of transportation - within the frame of Theory of Systems Alliances - are overviewed. Major attention is paid to the approaches utilizing sensitivity functions, predictive diagnostics and the fusion of them.

Keywords: Transportation systems, sensitivity, reliability, safety, resistance to failures, resistance to terrorist activity, human – machine – interaction

1. INTRODUCTION

Transportation is one of the most universal activities of human society. No part of the contemporaneous human population can live without that almost all its members move daily from one place to another (and back) and without permanent transportation of vast amounts of mass (food and other very wide spectrum of goods), energy and information. The some was true also for all human cultures in the history. Loosing of transportation possibilities (and information exchange) or its limitation from various political reasons results sooner or later in the necessary total degeneration of particular society or culture.

The realization of the need of free transportation possibilities for all members of human population, which is one of the conditions for its long time survival, represents a very complicated and difficult problem. At first:

- All such transportation activities (or at least the high majority of them) should be rational, oriented to support of fulfillment of some of the several fundamental needs of particular society survival – ensuring of its requirements on supply of food, energy, information, health care, acceptable environmental condition and security. Transportation activities, which do not serve for satisfying no of these needs act negative in principle and represent the chaotic component which should be minimized, if the particular society wish to live long and healthy.
- Even if these conditions are fulfilled, the amount of transportation rises proportionally (but not even in linear scale) to number of particular population members. The increasing size of transportation needs and resulting traffic density generated very high increase of requirements on transportation reliability and safety. Each fault in contemporary transportation systems projects in vast losses, not only financial but very often also on many people health and lives.

The operation safety and reliability improvement of large transport systems is therefore of the top interest for all the developed countries. One of the tools which can be successfully used to reach this goal is based on complex sensitivity investigation of the respective transportation system.

2. COMPLEX ADAPTIVE SYSTEMS

The nonlinear behavior of large scale transportation system alliance (for which is used here the name complex adaptive structures – CAS), is considered further as one of the main factors influencing their behavior. As one of the most important characteristics of CAS the resistance to disturbing influences has to be taken. Besides other possibilities how to improve the CAS operation reliability and safety the combination of sensitivity analysis with prediction diagnostics is taken into account before all. Such advanced approach allows the significant increase of CAS resistance to disturbing impacts targeted to the most sensitive parts. The road transportation system has to be considered as very complicated heterogeneous CAS. Of course, other kinds of transportation (railroad, air, water) operate also with complicated heterogeneous system alliances.

By the use of knowledge of system reliability theory, we can see that four principal approaches exist, which can be used for improving the operation reliability and safety of such large alliances. These are:

a) Increasing the quality of all components, functional blocks and alliance subsystems, from which these CAS are composed. This means to use preferably only the parts, realized by very good technology with very high quality control as concerns both their HW and SW parts, and as concerns the human subjects, interacting with technical transportation tools only very skilled and well trained, healthy and non-drowsy operators. Of course, this approach is known and used for many years but its main drawback is that it requires very high expenses.

b) Another possibility is based on the use of the system with reserves. This means that in the alliance of respective transportation systems such partial ones are inserted, which can replace the failing ones when necessary. Also this approach is known and used for long time.

c) Third possibility is based on the analysis of the values of the sensitivity of alliance functions to the changes of their parameter values and in subsequent optimizing of an alliance structure so that the very high values of sensitivities are minimized as much as possible. This approach can be considered as very sophisticated, but here existence of the theorem of the sensitivity invariance has to be taken into account. With respect to it, one can distribute the very high values of sensitivity between the eventual principally redundant parts. Of course, such an attempt requires also additional expenses. Nevertheless, the careful sensitivity analysis can form a rational basis for gaining of in reliability improved transportation system alliances.

d) The last, apparently most sophisticated approach, lays in application of principles of the so-called predictive diagnostics. Such an approach tries:

- to determine the regions of the system alliance parameters values in a respective parameter space (so called regions of acceptability RA),
- to analyze the trajectory *(t)* (life-curve) of the system alliance parameter values xi in the multidimensional space $X = \{xi\}$ and
- to predict, if and when the respective vector X approached dangerously to (or eventually crosses) the boundaries of RA.

Of course, none of these four approaches are universal in such a sense, that they can replace all the others. Actually, for design and creating the system alliances with very high operation reliability, various sophisticated combinations of all these approaches have to be used.

In this paper we go in detail as concerns the use of the combination of the last two mentioned approaches for proposing the methodology allowing significant enhancement of transportation systems alliances operation reliability and safety and also for reaching of their higher resistance to eventual failures and/or against attempts of their destruction either by natural or by criminal (terrorist) activities.

2. METHODICAL BACKGROUND

The US Transport Security Administration (TSA) suggest that the transportation system has to be considered as a set of interdependent links and nodes in which no element operation is safe if it can be influenced by a some other link characteristic with lower operation reliability and safety. Extension of this statement could be considered as the requirement to use the very high reliable and safe system elements, functional blocks or in alliance operating partial systems only. This orresponds to the strict application of the approach to the CAS reliability improvement.

This is evidently in contradiction with the well known experience, that there is in principle possible to construct reliable systems which include elements or blocks of lower reliability. This could be taken as the system reliability paradox. The explanation is hidden in the words: *…can be influenced…* of the above mentioned TSA suggestion.

This means, that in the operationally reliable system or system alliance there can be principally also used parts of lower reliability than in the required total reliability value, but the entire CAS structure must be arranged so, that the eventual failure of any CAS part does not have direct influence on the operation of the whole. Because any large transportation system requires its high operation reliability and safety, our strategy for improvement of these must be based on the proper combination of all three approaches.

Thus the transportation system has to be considered as the adaptive complex, i.e. as the alliance of partial systems consisting from interacting elements which adapt to each other over the time. The concept of such adaptive CAS was drawn also from a body of thought know as „complexity theory", which offers at least two additional insights.

- The respective CAS usually behaves with significant non-linearity, which means that certain small perturbations in the complex can sometimes project to large outcomes.

- The CAS displays „emergent properties“, which means that complex patterns can be based on seemingly random interactions among some or all elements of the respective CAS.

These insights are the key to understand why TSA´s mission is to enhance transportation safety (and security) while maintaining the free flow of commerce. Transportation system failures appear usually mostly randomly distributed over the system and its operation time, but in certain cases they can be more concentrated in some its parts or intervals of its operation time. Evidently, the knowledge of the space and time distribution of such failures is of very high use for the whole CAS reliability improvement. Such knowledge can be reached either by statistical analysis of the data measured on already existing CAS, or by theoretical analysis based on investigation of the sensitivities of CAS parts to change of on them influencing independent variables.

Both these approaches have their specific advantages and drawbacks (and therefore, both approaches have to be combined):

a) The respective measurement for reaching enough of statistical data is time-consuming and expensive and can not be provided without possibility of long-time interaction with considered really existing and operating CAS.

b) The investigation of the sensitivity values requires a vast amount of computations, especially if the respective system is more complicated and if it varies in the course of investigation.

As concerns the non-natural reasons of failures, the terrorists usually seek to inflict damage that is out of proportion to their efforts by attacking such parts of the system or system alliance, that will lead to non-linear consequences. In such cases the lost can be much higher than the effort, necessary for its origin. Such situation represent a very high danger for operation of respective CAS.

The knowledge of the eventually existence of such dangerous stages of investigated CAS belongs therefore to strategic knowledge. Terrorists naturally seek for such knowledge. TSA must guard against the risk that such situation in the considered CAS exist and if so, that the terrorist groups can reach the knowledge of them. In seeking to minimize the impact of respective safety and security measures, TSA seeks to ensure that the emergent patterns of commerce in free world economy are not disrupted by some such accidental events.

The public transport, especially the urban public transport, has to be described as an alliance of open systems in three hierarchical levels (see Fig. 1):

a) public transport infrastructure
b) transport processes
c) information system

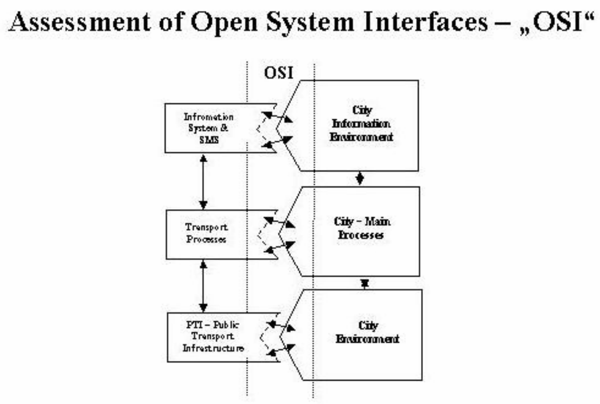

Fig. 1: Public transport system levels forming the open system

From the point of view of system analysis, the respective system alliance behavior during destructive impacts is very important. It represents therefore the object for systematic structural and sensitivity analysis.

3. SENSITIVITY ANALYSIS

Sensitivity analysis is a condition for safety and security management of CAS design. The resulting system function of the CAS under consideration can be generally expressed as

$$dF(dF1, dF2,\dots dFn), \qquad (1)$$

where the set of input factors is represented by vector of state variables:

$$dI(dI1,dI2,\dots dIn). \qquad (2)$$

To have the possibility of modeling the resulting functions, the form of matrix equation has to be recommended. It involves the matrix of sensitivities *S[sij]*, where elements *sij* corresponds to individual sensitivities of most important processes in the public transport. The output function of respective matrix equation of the operation phase x represents the input function of the phase *x+1*. The complex sensitivity matrix shown in the equation (1) is a good tool for the comparison of the main sensitivity values for to find the dominant one. The structural concept of system sensitivity analysis is based on the graph theory, especially on the sensitivity of transfer function of the graph on the individual branches in the graph structure and on finding the dominant sensitivity places in the whole CAS graph (finding the critical places in the structure). We can therefore write

$$\begin{bmatrix} dF_1 \\ dF_2 \\ dF_3 \\ \cdot \\ \cdot \\ \cdot \\ dF_n \end{bmatrix} = \begin{bmatrix} s_{11} & s_{12} & \cdot & \cdot & \cdot & \cdot & s_{1m} \\ s_{21} & s_{22} & \cdot & \cdot & \cdot & \cdot & s_{2n} \\ \cdot & & \cdot & & & & \cdot \\ \cdot & & & \cdot & & & \cdot \\ \cdot & & & & \cdot & & \cdot \\ \cdot & & & & & \cdot & \cdot \\ s_{n1} & s_{n2} & \cdot & \cdot & \cdot & & s_{nm} \end{bmatrix} \cdot \begin{bmatrix} dI_1 \\ dI_2 \\ dI_3 \\ \cdot \\ \cdot \\ \cdot \\ dI_n \end{bmatrix} \quad (3)$$

or in the simplified form:

$$[F] = [S] \cdot [I] \quad (4)$$

Sensitivity is expressed in relative scale, than the parameters are also relative values:

$$x_{ir} = \frac{x_1}{x_{\max}} \quad (5)$$

where *xmax* is the maximal value of the measure.
Relative Stress Sensitivity Matrix is defined through the equation:

$$F_{i,rel} = Sr_{ij} \frac{dx_j}{x_{j,\max}} \quad (6)$$

where

$$Sr_{ij} = \frac{dF_i}{dx_j} \cdot \frac{x_{j,\max}}{F_{io}} \quad (7)$$

where *Fi* is the relative change of influence of corresponding parameter in the component *i* and *dxj* is deviation of value *xj*. The coefficients of relative sensitivities can be replaced by fuzzy parameters, or in final form by fuzzy matrices. The respective fuzzy stages could be determined by expert evaluation into various numbers of groups.

$$S_{ij} \in \{1, 2 \ldots 5\} \quad (8)$$

In the table shown below (Tab.1), 5 groups are used.

Tab.1: The measures of fuzzy description - Sr_{ij}

x_j	Measure of influence	Sr_{ij}
1	No influence	0
2	Small influence	0,25
3	Middle influence	0,5
4	Remarkable influence	0,75
5	Dominant influence	1

Having used the so called „integral measure“ of the parameter influence, the time factor will be taken in the account.
The matrix equation has than form:

$$FM_{Ci}(T) = \frac{1}{T} \cdot \int_{t_2}^{t_1} \sum_{j=1}^{k} (Sr_{x_j}^{C_i} \cdot W(t) \cdot x_j(t)) dt \quad (9)$$

where *T = t1 – t2* is the time duration of the monitoring of system parameters in the vector *Ci* and the vector

$$M_C(T) = [M_{C1}(T), M_{C2}(T), \ldots M_{Cn}(T)] \quad (10)$$

is called the integral measure of influences of the set input state variables. Having finished the evaluation of sensitivity matrix parameters, the weakest system component can be subsequently determined.

4. TRANSPORT NETWORK TOPOLOGIES

According the TSA, different types of transportation systems operating in alliance could display different types of their network topologies. Nevertheless the respective networks can be classified in two basic categories:

- Scale-Free
- Random networks.

The „scale-free“ networks have nodes which possess a significantly higher concentration of connections than the average node. This type of network often resembles a hub and peer-to-peer systems and they are very robust when faced with naturally occurring errors, because the odds of a disruption hitting a key node are very low. However, these networks are very vulnerable to failures and attacks, because if a key node fails or is targeted, the disruption will affect the whole system. Similar discussion can be done also as concerns the topologies of the whole transportation systems alliances. The “random” networks do not have such disadvantage.

The tools of the network theory can also be applied to understanding to the possibility of terrorists’ activities. The terrorist groups organize themselves into almost random networks rather than into hierarchical structures because such networks tend to be more agile and resilient in response to their environments. Such networks are also more efficient in sharing information. Because all bureaucracies tend to handle ambiguity poorly, net-centric adversaries pose a particular problem for hierarchical bureaucracies. This is one of significant reasons why terrorist organizations try to exploit gaps between traditional bureaucracies.

TSA recognizes that it there seems to be necessary to take a network for to fight against a network. TSA is therefore working to strengthen our network character of government and industry partner operation style. Utilizing this approach, we will try in the course of later proposed research to identify the areas of greatest risk throughout transportation systems and/or its alliances and for to act as a prevention of unexpected failures or attacks and to mitigate their potential consequences.

5. CONLUSION

Transportation systems and their alliances play very important role in life of the contemporaneous human society. At present their significance graduates, almost in parallel with increasing of their complexity and also with the enhancement of requirements on their operation reliability and safety. The investigation of the respective transportation systems based on complex sensitivity can be successfully used to help to fulfill such a complex task.

Transportation systems themselves operate with very high degree of variability and therefore their properties and operation stages varies with time and other eventually significant independent variables. More over in some parts of transportation CAS these changes are more significant than in others, because of various local sensitivities, which values of course also change, often quite dynamically. Therefore a further aspect which seems to be very worthy for further research consists in the analysis of the time dependences of transportation system alliances sensitivities in different places of the CAS structure and of their changes due the influence of the most significant selection of other independent variables and of later optimization of this whole dynamic. Of course, the investigation of transportation system alliances in dynamic regime is much more laborious. Nevertheless, some introductory studies in this respect were already done (see [8,9,10] e.g.). We hope to be able to continue in the investigations.

6. ACKNOWLEDGEMENT

The research, which partial results are presented here was done in the range of the project No. IAA201240701 of the grant agency of the Academy of Sciences of the Czech Republic.

7. REFERENCES

[1] White Paper **- European transport policy for 2010: time to decide,** Office for official publications of the European communities, 2001.

[2] **Council Directive 91/440/EEC on the development of the Community’s railways**, Commission of the European Communities, Brussels, 29 July 1991.

[3] **Council Directive 96/48/EC on the interoperability of the trans-European high-speed rail system**, Commission of the European Communities, Brussels, July 23, 1996.

[4] **Directive 2001/14/EC of the European Parliament and of the Council on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification**, Commission of the European Communities, Brussels, February26, 2001.

[5] P**roposal for a Directive on safety on the Community's railways and amending Council Directive 95/18/EC on the licensing of railway undertakings and Directive 2001/14JEC on the allocation of railway infrastructure capacity and the levying of charges for the use of railway infrastructure and safety certification**, Commission of the European Communities, Brussels, June 2003.

[6]”Directive 2004/491EC of The European Parliament and of the Council of April 29, 2004 (Railway Safety Directive)”, **Official Journal of the European Union**, L164, pp 44-172, April 30, 2004.

[7] Moos, P., Malinovský, V.: **Workshop Berlin-Prague-Vienna:** “European Competence and Vision for Future, Transport Technologies", 22. 9. 2005, Brussels

[8] Novák M.: **Time dependencies of Systém Alliances Functions** (in Czech: Časové závislosti funkcí systémových aliancí), Research report No. V – 989/2007, to the grant No. IAA201240701, Dynamics of System alliances, GA AN CR, Prague, Apríl 2007

[9] Novák M., Votruba Z., Brandejský T.: **Alliances in heterogenous Network** (in Czech: Aliance v heterogenních sítích), Research report No. V – 1003/2007, and LSS 315/07 to the grant No. IAA201240701, Dynamics of System alliances, GA AN CR, Prague, November 2007

[10] Novák M., Moos P., Votruba Z.: **Dynamics of Sensitivity in Transportation System Alliances**, Research report No. V – 1020/2008, and LSS 325/08 to the grant No. IAA201240701, Dynamics of System alliances, GA AN CR, Prague, May 2008