Mivar models of reconstruction and expertise of emergency events of road accidents

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Abstract. The article deals with the problem of creating expert systems for the reconstruction and analysis of motor vehicle accidents (MVA). The need for development of the special expert system of the analysis and examination of road accident for the solution of this problem was formulated. Also, in the article the compatibility models of the Mivar Expert System and the abstract system of simulation modeling were described. In this article, the Mivar expert system "Analysis MVA" is considered as a promising solution for the reconstruction and analysis of traffic accidents. Much attention is drawn to the principles of operation of the mivar systems in the expert analysis of accidents.

1. Introduction
The number of cars in the world has been growing steadily over the years. If this trend continues, in Russia by 2020 the number of road motor vehicles per 1,000 inhabitants will reach 550 units. The stable increasing number of vehicles on the roads is one factor that raises the risk of accidents. It is estimated that every year more than a million people die from road traffic injuries around the world. An important aspect in the analysis of the accidents is the question of establishing the objective circumstances and causes of the accident with the assessment of the resulting traffic situation and the actions of the participants from a technical point of view. Such analysis allows creating a technical basis for identification of the perpetrators. For each case, it is necessary to consider all possible factors that could have an impact on the occurrence of the road transport situation. Therefore, there is a need to develop models of reconstruction and examination of road accidents \cite{1–4}. It is also worth noting that for the reconstruction of the car crash there is a need in a simulation model of the accident. It takes a lot of time to create a high-quality simulation model, as it is important to consider a huge number of parameters, their combinations, variations and interactions.

This article proposes to solve the problem of creating high-quality simulation models by using a specialized Mivar Expert System (MES) of analysis and expertise of accidents \cite{5}. The proposed system
will determine the optimal parameter values for the simulation. In other words, MES will allow experts to obtain the most reliable set of input parameters for a simulation modeling system (SMS) [6].

2. Models of compatibility of Mivar Expert and Simulation Systems
Let us consider models of compatibility of Mivar Expert and Simulation Systems to explain principles of work of MES [3–4]. \( P_{\text{exp}} = \{ P_{\text{exp}1}, P_{\text{exp}2}, \ldots, P_{\text{exp}n} \} \) denotes a set of parameters of MES. The set \( P_{\text{exp}} \) consists of a set of input parameters \( P_{\text{in}}^{\text{exp}} \) (\( P_{\text{in}}^{\text{exp}} \subseteq P_{\text{exp}} \)) and a set of output parameters \( P_{\text{out}}^{\text{exp}} \) (\( P_{\text{out}}^{\text{exp}} \subseteq P_{\text{exp}} \)).

\[ P_{\text{sim}} = \{ P_{\text{sim}1}, P_{\text{sim}2}, \ldots, P_{\text{sim}m} \} \] – a set of parameters of SMS. \( P_{\text{sim}}^{\text{in}} \) and \( P_{\text{sim}}^{\text{out}} \) are sets of input and output parameters of SMS (\( P_{\text{sim}}^{\text{in}} \subseteq P_{\text{sim}} \) and \( P_{\text{sim}}^{\text{out}} \subseteq P_{\text{sim}} \)). There are three types of models of compatibility of MES and SMS: MES is a dominant – a forward model: \( P_{\text{exp}} \rightarrow P_{\text{sim}}^{\text{in}} \); SMS is a dominant – a reverse model: \( P_{\text{sim}}^{\text{out}} \rightarrow P_{\text{exp}} \); an equivalent relation between MES and SMS – an equivalent model: \( P_{\text{exp}} \leftrightarrow P_{\text{sim}} \). We denote a set of forward and inverse models by \( M_{\text{exp} \rightarrow \text{sim}} \) and \( M_{\text{exp} \leftarrow \text{sim}} \) respectively. Then we get \( [P_{\text{exp}} \leftrightarrow P_{\text{sim}}] \in M_{\text{exp} \rightarrow \text{sim}} \cap M_{\text{exp} \leftarrow \text{sim}} \).

3. Structure of Mivar Expert System “Analysis MVA”
The Mivar model of MES “Analysis MVA” [7–8] consists of 16 classes, 144 parameters, 93 relations, 352 rules which include 109 restrictions. The structure of all classes, parameters, relations and restrictions is shown in Figure 1.

![Figure 1. Structure of the Mivar model of the system.](image-url)
The rules of the model are a set \( R_{\exp} = \{R_1, R_2, ..., R_{352}\} \):
\[
R_1(P_1) : P_1 = \frac{P_1}{P_2} \iff f = \frac{f_{\max}}{g}; \\
R_4(P_2, P_3, P_4) : P_1 = \frac{P_1 \cdot P_2}{P_4} \iff j_{\max} = \frac{f \cdot g}{K_3}; \\
R_7(P_2, P_3, P_{144}) \in P_3 = \sqrt{2 \cdot P_2 \cdot P_3 \cdot P_{144}} \iff V_0 = \sqrt{2 \cdot g \cdot f \cdot S_4}; \\
R_{352}(P_1, P_3) : P_{144} = \frac{P_3^2}{2 \cdot P_1} \iff S_4 = \frac{V_0^2}{2 \cdot j_{\max}}.
\]

\( C_{\exp} = \{C_1, C_2, ..., C_{109}\} \) is a set of restrictions of the model, where \( C_{\exp} \subseteq R_{\exp} \):
\[
C_1(P_1) : 0.08 \leq P_1 \leq 0.8 \iff 0.08 \leq f \leq 0.8; \\
C_2(P_1) : 1 \leq P_1 \leq 1.6 \iff 1 \leq K_3 \leq 1.6; \\
C_3(P_1) : P_1 \geq 0 \iff j_{\max} \geq 0; \\
\]
\[
C_{109}(P_{144}) : P_{144} \geq 0 \iff S_4 \geq 0.
\]

A set of parameters and rules \( \{P_{\exp}, R_{\exp}\} \) is used to build a Mivar network [9–13]. The network consists of the following elements of a bipartite oriented graph: vertex sets of first type (the parameters \( P_{\exp} \)), vertex sets of second type (the rules \( R_{\exp} \)) and edges of the graph that connect vertices from the first and second set (Figure 2) [14].

**Figure 2.** Algorithm of work MES “Analysis MVA”.

MES “Analysis MVA” is adaptive and represents a “white box” model. In another words, the expert has an access to change the knowledge base, add new rules (formulas) and parameters. It is also possible to change the existing parameters for individualization of the system. Therefore, the system is very flexible and allows the expert to create new scenarios for simulation of MVA.
4. Results of experimental researches

For our experiments we used the simulation system Virtual CRASH 3.0. The articles [1–7] discuss in detail the principles of collaboration of MES "Analysis MVA" and Virtual CRASH 3.0. As an example, let us consider the results of the experimental research of a road accident with a pedestrian. In this research, the name of the street was changed and a vehicle registration plate of the car was hidden in order to preserve anonymity.

Description of the motor vehicle accident: The car Toyota Yaris hit a pedestrian who crossed Kruglaya street on the right side. Kruglaya street was a two-way street. It was found that the driver was under the influence of alcohol. The reaction time of the driver was 1.5 seconds; the time delay actuation of the actuator was 0.3 seconds; the braking time was 0.2 seconds. The pedestrian's speed was 5 km/h. The pedestrian went along the lane of the car distance equal 1.4 meters. According to witnesses, the speed of the car Toyota Yaris at the time of collision was 50 km/h.

The road had the asphalt concrete pavement. The weather at the time of the accident was clear. The permitted maximum speed on this section of the road was 60 km/h. According to the results of measurements, the length of the brake track of the vehicle was 32 meters. The main force of the hit fell on the right front of the bumper and the hood of the car. The distance from the right edge of the road to the car was 2 meters. The overall width of the car is 1.66 meters.

The purpose of the research is to answer the question: “Did the driver have the technical abilities to avoid hitting the pedestrian?”.

Let us define the parameters of the road situation as follows: $V = 13.89 \text{ m/s}; V_p = 1.39 \text{ m/s}; t_1 = 1.5 \text{ s}; t_2 = 0.3 \text{ s}; t_3 = 0.2 \text{ s}; S_i = 32 \text{ m}; S_p = 2 \text{ m}; \Delta Y = 2 \text{ m}; B = 1.66 \text{ m}; f = 0.75; l_y = 0.7 \text{ m}; \text{SpeedLimit} = 60 \text{ km/h}$.

For ethical reasons, the photo materials of the accident were replaced with photos of the crash test of the event in question. The photos are presented in Figures 3, 4, 5 and 6.

Figure 3. Moment when the driver of the vehicle Toyota Yaris could see the pedestrian.

Figure 4. Moment of the first contact.

Figure 5. Braking of the vehicle.

Figure 6. Car damage.
The source data were entered into MES “Analysis MVA”. The initial data and the calculation results are shown in Figure 7.

Figure 7. Screenshot of MES “Analysis MVA”: source data and calculation results.

The solution search model is shown in Figure 8 as a graph.
The following is a listing of the solution search algorithm. The algorithm consists of 18 steps.

**Step # 0**

*Relation*: tv\_ly – pedestrian visibility time in the driver's field of vision [depends on ly]

*Rule*: tv\_ly – pedestrian visibility time in the driver's field of vision [depends on ly]

*Input parameters*:

- Vp (m/s)=1.39;
- ΔY (m)=2;
- ly (m)=0.7;

*Formula*:

\[ y = \frac{(x_1 + x_2)}{z} \]

*Result*:

\[ tv\_ly (s) = 1.94244604316547; \]

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Step # 1

Relation: Vo – vehicle speed before braking
Rule: Vo – vehicle speed before braking
Input parameters:
S4 (m)=32;
g (m/s²)=9.81;
f (0.08 - 0.8)=0.75;
Formula:
y=Math.sqrt(2*x1*x2*x3)
Result: Vo (m/s)=21.6997695840302;

Step # 2

Relation: Sv, Sv_ly
Rule: Sv_ly – pedestrian visibility distance (distance from the car to the collision) [depends on ly]
Input parameters:
lx (m)=0;
Vo (m/s)=21.6997695840302;
tv_ly (s)=1.94244604316547;
Formula:
y=x1*x2-x3
Result: Sv_ly (m)=42.1506315661017;

Step # 3

Relation: t∑ - total time
Rule: t∑ - total time
Input parameters:
t3 (s)=0.2;
t1 (s)=1.5;
t2 (s)=0.3;
Formula:
y=x1+x2+0.5*x3
Result: t∑ (s)=1.9;

Step # 4

Relation: t1, t2, t3, t4, jmax, jmax (without Kbe), S1, S2, Sp’, Sp’_ly, Sdr, Sim
Rule: jmax (without Kbe) - deceleration value without Kbe – brake efficiency correction factor
Input parameters:
g (m/s²)=9.81;
f (0.08 - 0.8)=0.75;
Formula:
y=x1*x2
Result: jmax (m/s²)=7.3575;

Step # 5

Relation: Ssw – length of the stopping distance
Rule: Ssw – length of the stopping distance
Input parameters:
jmax (m/s²) = 7.3575;
\( t_s^\sum \) (s) = 1.9;
Vo (m/s) = 21.6997695840302;

Formula:
y = (x₁ * x₂) + (Math.pow(x₂, 2)/(2 * z))

Result: Ssw (m) = 73.2295622096573;

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Step # 6
Relation: Sn, Sn_ly, La, Lb, M1, M2, ΔV, ΔV3, Vu, ΔV3 [depends on jsl], Vu [depends on jsl], OverSpeed V, OverSpeed Vo, OverSpeed Vo_additional
Rule: Sn_ly – distance that the car will move after crossing the line of the trajectory of the pedestrian if the driver starts to brake in a timely manner [depends on ly]

Input parameters:
Ssw (m) = 73.2295622096573;
Sv_ly (m) = 42.1506315661017;

Formula:
y = x₁ - x₂

Result: Sn_ly (m) = 31.0789306435556;

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Step # 7
Relation: Vn, Vn_ly
Rule: Vn_ly – speed of the car at the time of crossing the line of the trajectory of the pedestrian if the driver starts to brake in a timely manner [depends on ly]

Input parameters:
Sn_ly (m) = 31.0789306435556;
jmax (m/s²) = 7.3575;

Formula:
y = Math.sqrt(x₁ * x₂)

Result: Vn_ly (m/s) = 15.1216147355354;

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Step # 8
Relation: t₁, t₂, t₃, t₄, jmax, jmax (without Kbe), S1, S2, Sp’, Sp’_ly, Sdr, Sim

Rule: tₙ, tₙ’_ly
Rule: tₙ’_ly – time of movement of the car from the moment of occurrence of the dangerous situation crossing the line of the trajectory of the pedestrian (if the driver starts to brake in a timely manner) [depends on ly]

Input parameters:
Vn_ly (m/s) = 15.1216147355354;
jmax (m/s²) = 7.3575;
\( t_s^\sum \) (s) = 1.9;
Vo (m/s) = 21.6997695840302;

Formula:
y = x₁ + ((x₂ - x₃)/z)

Result: tₙ’_ly (s) = 2.79407473306079;

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Step # 9
Relation: t₁, t₂, t₃, t₄, jmax, jmax (without Kbe), S1, S2, Sp’, Sp’_ly, Sdr, Sim
**Rule:** $\text{Sp’}_\text{ly}$ – movement of the pedestrian during $\text{tn’}_\text{ly}$

**Input parameters:**
- $\text{tn’}_\text{ly} (s)=2.79407473306079$;
- $V_p (m/s)=1.39$;

**Formula:**
$$y=x_1 \times x_2$$

**Result:** $\text{Sp’}_\text{ly} (m)=3.8837638789545$;

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**Step # 10**

**Relation:** $\text{Sls}\_\text{truck, Sls}\_\text{auto}, \Delta X, L, M, \text{Sfragments, Vo, ton, Vca}$

**Rule:** $\Delta X$ – sum of the distances from the lateral surface of the vehicle to the boundary of the danger zone and the width of the track of the vehicle

**Input parameters:**
- $\Delta Y (m)=2$;
- $B (m)=1.66$;

**Formula:**
$$y=x_1 + x_2$$

**Result:** $\Delta X (m)=3.66$;

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**Step # 11**

**Relation:** $P (\text{Sp’} < \Delta X, \text{Sp’} > \Delta X), P\_\text{ly} (\text{Sp’}_\text{ly} < \Delta X, \text{Sp’}_\text{ly} > \Delta X)$ – traffic accident prevention

**Rule:** $\text{Sp’}_\text{ly} < \Delta X, \text{Sp’}_\text{ly} > \Delta X$

**Input parameters:**
- $\text{Sp’}_\text{ly} (m)=3.8837638789545$;
- $\Delta X (m)=3.66$;

**Formula:**
if $(x<y)$ \{z = ‘Sp’ $\Delta X$, condition of unsafe crossing of the vehicle trajectory’;\} else \{z = ‘Sp’ $\Delta X$, condition of safe crossing of the vehicle trajectory’;\}

**Result:** $P\_\text{ly} (\text{Sp’}_\text{ly} < \Delta X, \text{Sp’}_\text{ly} > \Delta X)=\text{Sp’} > \Delta X$, condition of safe crossing of the vehicle trajectory;

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**Step # 12**

**Relation:** $\text{Vo}_{\text{additional}}$ – vehicle speed before braking, considering the additional speed $V$ at the time of collision of the vehicle

**Rule:** $\text{Vo}_{\text{additional}}$ – vehicle speed before braking, considering the additional speed $V$ at the time of collision of the vehicle

**Input parameters:**
- $V (m/s)=13.89$;
- $\text{Vo} (m/s)=21.6997695840302$;

**Formula:**
$$y=\sqrt{\text{Math.pow}(x1,2)+\text{Math.pow}(x2,2)}$$

**Result:** $\text{Vo}_{\text{additional}} (m/s)=25.7645512283835$;

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**Step # 13**

**Relation:** Conversion $V (m/s) \rightarrow V (\text{km/h})$

**Rule:** $\text{Vo}_{\text{additional}} (m/s) \rightarrow \text{Vo}_{\text{additional}} (\text{km/h})$

**Input parameters:**
Vo_additional (m/s)=25.7645512283835;
Formula:
y=(x*3600)/1000
Result: Vo_additional (km/h)=92.7523844221808;

Step # 14
Relation: SpeedLimit - maximum speed limit
Rule: Analysis SL Vo_additional – parameter that determines the driver's violation of the speed limit, considering Vo_additional
Input parameters:
SpeedLimit (km/h)=60;
Vo_additional (km/h)=92.7523844221808;
Formula:
if (x1 >= x2) {y = 'Vehicle speed V (km/h) ≤ SpeedLimit, The driver observed the speed limit';} else {y = 'Vehicle speed V (km/h) > SpeedLimit, The driver did not observe the speed limit';
Result: Analysis SL Vo_additional=Vehicle speed V (km/h) > The driver did not observe the speed limit;

Step # 15
Relation: P (tv < t∑, tv > t∑), P_ly (tv_ly < t∑, tv_ly > t∑) – traffic accident prevention
Rule: tv_ly < t∑, tv_ly > t∑ – the driver had the technical ability to prevent an accident
Input parameters:
tv_ly (s)=1.94244604316547;
t∑(s)=1.9;
Formula:
if (x<y) {z = 'tv <t∑, The driver did not have the technical ability to prevent an accident';} else {z = 'tv > t∑, The driver had the technical ability to prevent an accident';
Result: P_ly (tv_ly < t∑, tv_ly > t∑)=tv > t∑, The driver had the technical ability to prevent an accident;

Step # 16
Relation: Sn, Sn_ly, La, Lb, M1, M2, ΔV, ΔV3, Vu, ΔV3 [depends on jsl], Vu [depends on jsl], OverSpeed V, OverSpeed Vo, OverSpeed Vo_additional
Rule: OverSpeed Vo_additional – exceeding the maximum speed Vo_additional
Input parameters:
Vo_additional (km/h)=92.7523844221808;
SpeedLimit (km/h)=60;
Formula:
y=x1-x2
Result: OverSpeed Vo_additional (km/h)=32.7523844221808;

Step # 17
Relation: P (Ssw < Sv, Ssw > Sv), P_ly (Ssw < Sv_ly, Ssw > Sv_ly), P (Ssw < Sp, Ssw > Sp) – traffic accident prevention
Rule: Ssw < Sv_ly, Ssw > Sv_ly
Input parameters:
Ssw (m)=73.2295622096573;
Sv\_ly (m)=42.1506315661017;
Formula:
if (x<y) \{z = 'Ssw < Sv, The driver had abilities to prevent the accident by timely braking';\} else \{z = 'Ssw > Sv, The driver did not have abilities to prevent the accident by timely braking. The vehicle was not able to stop in front of the pedestrian's trajectory';\}
Result: P\_ly (Ssw < Sv\_ly, Ssw > Sv\_ly)=Ssw > Sv, The driver did not have abilities to prevent the accident by timely braking. The vehicle was not able to stop in front of the pedestrian's trajectory;

Using MES “Analysis MVA” we get the following results:
1) The driver had technical abilities to prevent the accident (t_v > t\_\sum = 1.94 s > 1.90 s).
2) Since the condition S_{sw} > S_v = 73.22 m > 42.15 m is met, the vehicle did not stop in front of the pedestrian's trajectory. As a result, the pedestrian was hit by the vehicle.
3) The pedestrian could have left the danger zone if he had changed his speed and direction of the movement \(S'_p > \Delta X = 3.88 m > 3.66 m\).
4) The driver did not comply with the speed limit and exceeded the maximum speed limit by 32.75 km/h \(V_o > SpeedLimit = 92.75 km/h > 60 km/h\).

In order to get a complete picture of the situation, we used the results obtained from MES “Analysis MVA” for the reconstruction of the accident in Virtual CRASH 3.0. Figure 9 shows the reconstruction [15] of the accident events.

Figure 9. Reconstruction of the accident.

The conclusion is thus that the driver acted technically wrong and he is completely guilty of the accident.

5. Conclusion
The Mivar Expert System “Analysis MVA” [8] helps to reduce the complexity of the process of analysis and reconstruction of disputed motor vehicle accidents [16–17], to minimize the occurrence of errors in the calculation, to save human resources on experts and to improve the speed in decision-making [3–4].

In the future, the developed mivar mathematical models [18–19] of reconstruction and expertise of road accidents can be used in autonomous transport [20–23]. This will allow law enforcement agencies
to automatically determine the cause and culprits of the accident and to form the conclusion with detailed information about the technical prerequisites of the accident.

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