Improving the quality of the investigation of a road traffic accident

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Abstract. The article deals with the issue of improving the quality of auto expertise and as a result, with the issue of investigating road accidents. The main parameter used in the auto expertise is vehicle deceleration. But today we consider the characteristics of the roadway and the load of the car when decelerating a car. As for temperature factor it is not only ignored, but the possibility to take it into account doesn’t even exist. The impact of the ambient temperature on vehicle deceleration was studied. There was simulation of vehicle braking which physically justified the impact of ambient temperature. On the basis of the practical tests conducted, the dependence of vehicle deceleration on the ambient temperature was determined. This dependence will allow auto experts make calculations more objectively which will positively affect not only the course of road accident investigation but also the identification of factors conducive to development and emergence of the accident.

1. Introduction
Addressing road transport accidents involves a set of preventive measures a special place among which belongs to the study of the road accident causes. Auto expertise allows justice system to establish these reasons in full since it takes into account not only the existing legal but also technical aspects. The technical ability of the participants in the accident to prevent the accident is determined. In conducting technical calculations vehicle deceleration is one of the main parameters used to influence all the calculations. The expert chooses this parameter individually based on the available characteristics of a vehicle. Thus, the validity and accuracy of the deceleration value selected by an expert may affect not only the results of the auto expertise conclusions but also the lives of the accident participants [11].

2. Relevance and scientific value of the article with a brief review of the literature
At present, if it is not possible to experimentally establish the deceleration value by the expert divisions of the Ministry of Justice and the Ministry of Internal Affairs of Russia it is selected from the corresponding tables (Table 1). Moreover, the selected parameter will depend on the following factors: type of road surface, vehicle category and load. All the other factors are not possible to take into account for choosing the deceleration value [10].
Table 1. The values of the established deceleration of M1 vehicle on the roadway part with adhesion coefficient of $\varphi=0.7$.

| Vehicle category | The values of the established vehicle deceleration, m/s² |
|------------------|----------------------------------------------------------|
|                  | Without load | 50% load | 100% load |
| M1               | 6.8          | 6.6      | 6.3       |

The value of the established deceleration is influenced by various external factors, including the model of the car, the type of tires rubber, the type and condition of the road surface, the ambient temperature, etc. Let us estimate one of them namely the ambient temperature and its impact on the value of the established vehicle deceleration.

The factors that characterize the road surface, its wear and condition have the greatest effect on the deceleration. Temperature is the next most influential factor. This statement that the ambient temperature, all things being equal, influences the vehicle deceleration is reflected in the works of A. A. Kochetkov, E.V. Balakin, S.A. Evtyukov and other authors [2].

In addition, the systematic study of vehicle braking process shows quite a noticeable influence of ambient temperature on the deceleration, especially at low temperatures.

3. Statement of the problem

Vehicle deceleration during braking determined mainly by the adhesion coefficient of the tire to the road surface depends on a large number of factors (the condition of the tire tread and the road surface). It might be therefore asked to what extent the influence of the ambient temperature on vehicle deceleration value (and accordingly, the stopping distance) is physically justified.

In this regard, we perform a simulation of vehicle braking in order to determine the temperature in the area where the tire contacts the road as well as the possible influence of the ambient temperature on it.

We will carry out practical tests by which we will establish the dependence of vehicle deceleration on the ambient temperature.

4. Theoretical part

First of all, it should be noted that the temperature in the area where the tire contacts the road surface during vehicle movement is not equal to the ambient temperature but is determined by two points:

First, the tire of the vehicle wheel is warmed up in the process of movement (without braking) due to its deformation, which is accompanied by irreversible loss of energy;

A lot of papers are devoted to the problem of tire heating during car rolling [15, 19].

The loss of energy $Q$ spent on heating the material is usually measured as:

$$Q = Q_0 \varepsilon^2$$  \hspace{1cm} (1)

where $\varepsilon$ - amplitude of the variable strain; $Q_0$ - proportionality coefficient.

$Q_0$ value has a very complex structure and it is determined not only by friction inside the rubber-like material but also due to internal friction between the various components of the complicated composite tire structure (micro-friction between dissimilar layers, between the matrix and the fibers of the reinforced parts of the composite).

Let us choose a heat source $Q$ which provides a qualitative match with experimental data.

The wheel consists of a hollow tire heated by deformation. The inner part of the wheel is a metallic disc. The heat released inside the tire is discharged into the air that fills the tire as well as into the metal forming the basis of the wheel. Then it is transferred to the surrounding air both from the outer surface of the tire and from the surface of the metal part of the wheel. The scheme of the heat flows is presented on Figure 1 [14].
Figure 1. Scheme of the wheel heat flows.

$T_{\text{outer}}$ - is the ambient temperature; $T_{\text{air}}$ - is the air temperature inside the tire; $T_m$ - is the temperature of the metal disc of the wheel; $T_t$ - is the tire temperature. Heat flows are denoted as: $q_1$ - is the flow from the tire into the environment; $q_2$ - is the flow from the metal disc into the environment; $q_3$ - is the flow from the tire to the air filling the tire; $q_4$ - is the flow from the tire to the metal disc of the wheel.

The temperature distribution in the tire is described by the equation of transient thermal conductivity:

$$\rho C_i \frac{\partial T_t}{\partial t} + \nabla (\lambda \nabla T_t) = Q$$ \hspace{1cm} (2)

- temperature; $\rho$, $C_i$, $\lambda$ - is density, heat capacity and coefficient of thermal conductivity, respectively; $Q$ - is heat generation inside the tire due to deformation; $t$ - is time.

Equation (2) should be solved under the following initial and boundary conditions:

$T(0) = T_{\text{outer}}$ (initial temperature = ambient temperature);

$$-\lambda \frac{\partial T_t}{\partial n} = h_{t,\text{outer}} (T_{\text{outer}} - T_t)$$ \hspace{1cm} (3)

$$-\lambda \frac{\partial T_t}{\partial n} = h_{t,\text{air}} (T_{\text{air}} - T_t)$$ \hspace{1cm} (4)

$$-\lambda \frac{\partial T_t}{\partial n} = h_{t,m} (T_t - T_m)$$ \hspace{1cm} (5)

Relations (3) - (5) determine the heat transfer from the tire to the environment, from the tire to the air inside the tire and from the tire to the metal disc, respectively. The heat transfer coefficients $h_{t,\text{outer}}$, $h_{t,\text{air}}$, and $h_{t,m}$ determine the heat transfer from the tire into the surrounding air, the heat transfer from the tire to the air inside the tire and the heat transfer from the tire to the metal disc, respectively [16].

Similarly, the temperature distribution in a metal disc is described by the following equation:

$$\rho_m C_m \frac{\partial T_m}{\partial t} + \nabla (\lambda_m \nabla T_m) = 0$$ \hspace{1cm} (6)

Unlike equation (3), there is no term defining the internal heat source here while the other symbols correspond with those in equation (3). The boundary conditions for equation (7) are:

$$-\lambda_m \frac{\partial T_m}{\partial n} = h_{m,\text{outer}} (T_{\text{outer}} - T_m)$$ \hspace{1cm} (7)

$$-\lambda_m \frac{\partial T_m}{\partial n} = h_{m,\text{air}} (T_m - T_t)$$ \hspace{1cm} (8)

Condition (7) determines the rejection of heat from a metal disc into the surrounding air with the corresponding heat transfer coefficient $h_{m,\text{outer}}$.

Condition (8) determines the heat transfer from the tire to the metal disc of the wheel.

We shall notice that since the heat conduction problem for solids (tires and metal disc) is further solved with a joint boundary, conditions (5) and (8) become redundant because the equality of heat flows...
on the adjacent boundary between solids is performed automatically. Naturally, the tire and wheel disc are characterized by their thermal properties (density, heat capacity and thermal conductivity) [5].

We consider the air inside the tire as a kind of abstract body that can be heated by heat transfer from the tire to this body. Therefore, the heating equation of this abstract body with the thermophysical air properties should be added to the heat conduction equation (8):

\[
\rho_{\text{air}} C_{\text{air}} V_{\text{air}} \frac{dT_{\text{air}}}{dt} = q_{\text{air}} = h_{\text{air}} (T_{\text{air}} - T_{\text{ambient}}) S_{t},
\]

where \( q_{\text{air}} \), \( C_{\text{air}} \), \( V_{\text{air}} \) is density, heat capacity and air volume inside the tire; \( S_{t} \) - is the area of the inner surface of the tire.

The term on the right represents a heat source which is characterized by the boundary condition (4).

We will solve the problem of heating the metal rim as a whole since the transfer of heat from the tire to the metal will be limiting due to the high thermal diffusivity of the metal:

\[
\rho_{\text{m}} C_{\text{m}} V_{\text{m}} \frac{dT_{\text{m}}}{dt} = q_{\text{m}} = h_{\text{inner,m}} (T_{\text{m}} - T_{\text{ambient}}) S_{t} - h_{\text{outer,m}} (T_{\text{m}} - T_{\text{ambient}}) S_{t},
\]

Thus, equations (2), (9) and (10) are to be numerically solved with respect to three unknown variables \( T_{t} \), \( T_{m} \) and \( T_{\text{air}} \). For an equation with partial derivatives the boundary conditions are determined by relations (3), (4) and (5). For ordinary differential equations boundary conditions are not required.

As the initial conditions for \( T_{t} \), \( T_{m} \) and \( T_{\text{air}} \) we simply choose the equality of these temperatures to the ambient temperature at the beginning.

To complete the problem statement it is required to set the heat transfer coefficients \( h_{\text{air,t}} \), \( h_{\text{air}} \) and \( h_{\text{outer,m}} \).

The conditions of convective heat transfer are set by the boundary conditions (3), (7) and the convention coefficient \( h_{c} \). Convection coefficients are determined by thermophysical properties (thermal conductivity, density and viscosity) and are expressed in terms of the Nusselt number, \( \text{Nu} \) [6]:

\[
h_{c} = \frac{\text{Nu} \cdot \lambda}{d_{c}}
\]

where \( d_{c} \) - is the typical size of the body streamlined by the flow;

The Nusselt number in its turn also depends on the parameters of the blowing air flow.

This dependence is determined by the Reynolds number, \( \text{Re} \):

\[
\text{Nu} = \zeta \cdot 0.018 \cdot \text{Re}^{0.8}
\]

where \( \zeta \) - is the correction for the channel curvature which is determined by the ratio of the channel radii and its external curvature

\[
\zeta = 1 + 1.8 \left( \frac{2d_{\text{ch}}}{d_{c}} \right)
\]

where \( d_{\text{ch}} \) is the diameter of the channel (pipe), \( d_{c} \) is the diameter of curvature.

The Reynolds number which is the ratio of inertia forces to viscous forces in a flow is calculated in the usual way:

\[
\text{Re} = \frac{V \cdot d_{c}}{\mu}
\]

where \( V \) - is the typical speed; \( d_{c} \) - is the typical size, \( \mu \) - is the coefficient of dynamic viscosity.

The energy of the heat source \( Q \) is determined by the deformation of the tire which is concentrated mainly in the area where the tire contacts the road. The heat released in the contact area is transferred along with the wheel rotation. Therefore, the heat source for each point of the tire should be represented as a stage periodic function, and the convective term of heat transfer from the contact area should be added to the heat conduction equation (8). Since wheel rotation is rather quick the typical heat distribution in the tire due to its thermal conductivity takes much less time than the transfer due to the
wheel rotation. That’s why value $Q$ might be considered as a constant equal to the heat average generated in the tire per time unit [3].

We used Comsol Multiphysics pack to solve the problem concerning the temperature $T$ in the tire and the temperature $T_t$ [4].

After selecting the value of the heat source $Q$ the calculations for different values of the ambient temperature were made ($-10^\circ$C, 0°C, 10°C, 20°C, 30°C) that are shown on Figure 2.

![Figure 2. Tire heating for different values of the ambient temperature.](image)

It is clear that these data correspond to a certain tire with its thermophysical and mechanical properties and to a certain road surface which was tested. These results may differ to some extent for other tires and road conditions.

Thus we can see that the ambient temperature significantly determines the temperature of the tire after a long distance travelled by the vehicle.

In the course of rolling the tire is approximately heated by $10 – 30^\circ$C which means its temperature differs from the ambient temperature but finally, all things being equal, it will be higher than the ambient temperature.

The process of tire heating when sliding down the road is determined by the equation of heat conduction that is similar to equation (9). The term of the heat source $Q$ is absent here owing to heat release in its cyclic deformation during rolling:

$$\rho C \frac{\partial T}{\partial t} + \nabla (\lambda \nabla T) = 0 \quad (15)$$

Instead, a surface heat source $Q_s$ is added which might be estimated as the kinetic energy of the vehicle $mv^2/2$ at the beginning of its full braking and it should turn into thermal energy until the vehicle stops.

The tire is supposed to be stationary in the model while the road and the surrounding air are moving towards (in the direction opposite to the real vehicle movement) at speed $V$, which varies from the initial speed $V_0$ to zero.

There is a surface heat source in the contact area which is characterized by the kinetic energy of the vehicle. Heat from the surface source is distributed into the tire volume from which it is released into the environment due to convection, transferred to the air inside the tire and to the metal disc corresponding to the wheel rim. A convective term providing heat removal from the contact area shall be added to the heat conduction equation for the road:

$$\rho C \left( \frac{\partial T}{\partial t} + V(t) \cdot \nabla T \right) + \nabla \cdot (\lambda \nabla T) = 0 \quad (16)$$

The initial temperature of the tire $T_t$ is equal to the temperature of its heating as a result of rolling and the initial temperature of the road $T_r$ equals to the ambient temperature $T_{ambient}$:

$$T_t(0) = T_{ambient}, \quad T_r(0) = T_{ambient} \quad (17)$$
When we solve the problem of the heat flows equality at the boundary between two bodies (tire and road) the boundary conditions are determined automatically in the contact area. The condition of heat transfer from the tire to the metal wheel is automatically performed, as well. The remaining boundary conditions correspond to the heat exchange with the environment:

$$-\lambda \frac{dT}{dn} = h(T - T_{\text{ambient}})$$

where the heat transfer coefficient $h$ is different for the tire and the road.

The stated problem was solved with the help of Comsol Multiphysics pack which is shown on Figure 3.

**Figure 3.** Temperature distribution in the area the tire contacts the road at initial vehicle speed of 60 km/h.

The tire temperature in the contact area at various ambient temperatures is shown on Figure 4.

**Figure 4.** Temperature distribution along the contact area at different ambient temperatures.

Thus, it is physically justified that the ambient temperature (all things being equal) will noticeably determine the final temperature in the contact area. This means that the specialists should take into account the impact of the ambient temperature while conducting auto expertise.

Practical relevance, suggestions, results of implementations and experimental studies 7560 practical tests were carried out in order to establish the dependence of the vehicle deceleration on the ambient temperature [9]. Based on those tests, it has been determined that the vehicle deceleration decreases when we use summer tires what can be described by the piecewise linear dependence on Figure 5.
It follows that all subsequent data characterizing the mechanism of the incident, in the calculation of those there is a parameter of the established vehicle deceleration will also change depending on the ambient temperature.

At minus temperatures below -5 °C if the vehicle was equipped with summer tires the established vehicle deceleration value of all the investigated vehicles would remain unchanged and equal to $j_{-5}$.

With an increase of the ambient temperature from -5 °C to 20 °C, deceleration had been rising by linear principle until $j_{20}$ was reached. A further increase of temperature from 20 to 30 °C had practically no effect on the established vehicle deceleration value. Such a course of the studied process suggests that the law of the change of the established deceleration depending on the ambient temperature can be described by a piecewise linear dependence

$$j = \begin{cases} j_{-5} & \text{at } t < -5 \ ^\circ \text{C} \\ j_{-5} + at & \text{at } -5 \ ^\circ \text{C} \leq t \leq +20 \ ^\circ \text{C} \\ j_{20} & \text{at } t > +20 \ ^\circ \text{C} \end{cases} \quad (19)$$

The use of regression analysis allowed us to estimate the value of $a$ coefficient (slope ratio). It turned out to be equal $a = 0.07 \text{ m/s}^2$ for almost all types of vehicles. The values of $j_{\cdot}$ varied over a larger range and they obviously depend on the physical and mechanical properties of the road surface and the wheels rubber of the vehicle. With an increase of the ambient temperature from -5 °C to +20 °C, the established deceleration rises. Consequently, when we choose the established deceleration value without adjustment to the ambient temperature our calculations can be incorrect distorting the real picture of events, and giving a wrong assessment to the actions of the road accident participants [1].

The studied dependence will not only help improve the objectivity of auto expertise, but also the quality of the road accidents investigation which will allow a truly innocent person to avoid punishment, and vice versa, those whose actions caused the incident to bear responsibility for their actions. The absence of more precise parameters objectively reflecting the influence of one or another factor, in this case the temperature factor, makes the process of investigating the true causes of the accident not only meaningless but also dangerous [9]. In the conduct of auto expertise not only the question of the conformity of the actions of accident participants is examined but all circumstances of the accident as a whole. The necessary and sufficient conditions for the emergence and further development of the accident are established, too. In case false conditions contributing to the emergence and further development of the accident are identified, the measures aimed at eliminating and reducing the risk of a similar accident repetition at the same site may not only have any practical impact, but also have the opposite effect.

![Figure 5](image-url)
5. Findings (conclusion)
We performed the vehicle braking simulation during which it was determined that the ambient temperature affects the final temperature in the contact area and as a result the vehicle deceleration.

Practical tests have been carried out based on which we have established the dependence of the vehicle deceleration on the ambient temperature with summer tires and with various vehicle loads.

The obtained results allow the experts to qualitatively improve the conclusions of the auto expertise. This will help to avoid misunderstandings in the investigation of road accidents and will eliminate the factors that really affect not only the emergence but also the development of those accidents.

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