Efficiency enhancement of the vehicle fuel tank ventilation system by improving its architecture and design

V V Glaviznin, G G Ter-Mkrtichyan and N A Mikerin
Fuel systems department, FSUE "NAMI", Moscow, Russian Federation
E-mail: vladimir.glaviznin@nami.ru

Abstract. Hydrocarbon emissions from fuel evaporation contribute significantly to the total emissions of harmful substances from vehicles with forced spark ignition. To meet the legally established standards for limiting hydrocarbon emissions from evaporation, all current vehicles use fuel vapor control systems. The design of the system can vary and depends on the sales market of a particular vehicle. This article describes the development of this system for the market of the Russian Federation, as well as optimization for promising sales markets with more stringent environmental requirements.

1. Introduction
In addition to the toxic substances generated by the combustion of fuel, vehicles equipped with forced-ignition engines generate a certain amount of hydrocarbons in the form of fuel vapors formed as a result of evaporation from the fuel system, the main element of which is the fuel tank. The share of hydrocarbon emissions from evaporation can reach up to 20% of the total hydrocarbon emissions [1, 2]. To capture the hydrocarbons formed as a result of fuel evaporation, a fuel vapor control system is used on modern vehicles.

Despite the many design options for this system from different automakers, the principle of its operation is the same in all cases. The system for control fuel vapors from the tank is based on a carbon canister (canister filled with specially prepared activated carbon), which accumulates fuel vapors, preventing them from entering the atmosphere. At certain operating modes, fuel vapors from the carbon canister are fed into the engine intake tract, after which, mixing with the air, they burn up during the operation of the engine.

2. Results
The general scheme of the fuel vapor capture system is shown in Figure 1.

In Europe and the Russian Federation, the standards for hydrocarbon emissions from evaporation are established by regulations based on UN Regulation No. 83, Type IV. At the moment, the Russian Federation has standards that comply with the Euro 6 standards for hydrocarbon emissions from evaporation, in which the maximum permissible values are set at 2 g from the vehicle per test. To quantify the emissions of hydrocarbons from evaporation, a test is performed in the SHED chamber, after the vehicle runs on running drums in the laboratory according to specially established driving cycles.
To comply with these standards, it is first necessary to determine the sufficient working capacity of the main component of the fuel vapor control system - the carbon canister. The working capacity of the carbon canister depends primarily on the brand of activated carbon used and its volume. The required working capacity is calculated based on the characteristics of the activated carbon used, the refueled volume of the fuel tank, the type of fuel, and the calculated amount of vapor.

The work on modeling the amount of steam generated by gasoline evaporation was first undertaken by Wade in the 1960s, who established equations relating the formation of vapor to an increase in fuel temperature and certain properties of the fuel, including Reid vapor pressure (RVP), distillation properties, density, and molecular weight (Wade, 1967) [3]. These equations were used by the US Environmental Protection Agency (EPA) for earlier versions of calculated vehicle emissions models. In the 1980s, Reddy developed a simplified model of vaporization based only on fuel temperature rise and RVP, and published model coefficients reflecting variations in altitude (sea level and Denver, Carolina) and ethanol content (E0, E10) [4, 5]

\[ TVG = A e^{B \cdot RVP} (e^{CT_2} - e^{CT_1}) \]

where TVG – fuel vapor generation per day in relation to the volume of the tank vapor space [g/gallon]; RVP – Reid vapor pressure [psi]; T1 – initial temperature [°F]; T2 – final temperature [°F]; A, B, C – constants that depend on the altitude above sea level and the ethanol content in the fuel in the US system of units.

The equation applies only when the vehicle is parked, when the temperature rise is recorded. In the event that there is a constant decrease in temperature (for example, after reaching the daily maximum value), it is conditionally assumed that no vapors are formed in the fuel tank.

Table 1 shows the values of the constants for different gasolines and the two positions of the vehicle. One is at sea level, and the other is at an altitude of 1,609 m (Denver, Carolina).
Table 1. Wade-Reddy constant equations in the US system of units.

|       | E0          | E10          |       | Sea Level 1,609 m | Sea Level 1,609 m |
|-------|-------------|--------------|-------|-------------------|-------------------|
| Conditions |            |              |       |                   |                   |
| A     | 0,00817     | 0,00518      | A     | 0,00875           | 0,00665           |
| B     | 0,2357      | 0,2649       | B     | 0,2056            | 0,2228            |
| C     | 0,0409      | 0,0461       | C     | 0,0430            | 0,0474            |

By converting equation (1) and replacing the US units with SI units, we obtain the equation

\[ TVG = A e^{R \cdot (e^{C t_2} - e^{C t_1})}, \]  

(2)

where TVG – fuel vapor generation per day in relation to the volume of the tank vapor space [g/liter]; RVR – Reid vapor pressure [kPa]; \( T_1 \) – initial temperature [°C]; \( T_2 \) – final temperature [°C]; A, B, C – constants that depend on the altitude above sea level and the ethanol content in the fuel in the SI system of units.

Table 2. Wade-Reddy constant equations in the SI system of units.

|       |            |              |       |                   |                   |
|-------|-------------|--------------|-------|-------------------|-------------------|
| Conditions |            |              |       |                   |                   |
| A     | 0,00817     | 0,00518      | A     | 0,00875           | 0,00665           |
| B     | 0,2357      | 0,2649       | B     | 0,2056            | 0,2228            |
| C     | 0,0409      | 0,0461       | C     | 0,0430            | 0,0474            |

As a result of mathematical modeling, using the main parameters included in the formula (2), the necessary working capacity of the carbon canister was calculated [6]. Based on the results of the calculation, a two-chamber carbon canister was developed, the scheme of which is shown in Figure 2.

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**Figure 2.** Two-chamber carbon canister of the UMP. a - fuel vapor intake from the fuel tank; b - fuel vapor output to the engine during purging; c - connection to the atmosphere.

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\(^1\) Formulas used \( p_{psi} = 0,145 p_{kPa} \), \( t_F = \frac{9}{5} t_C + 32 \), \( V_{gal} = 3,7854 V_l \).
For the full functioning of the carbon canister and the fuel vapor control system as a whole, in addition to the working capacity of the carbon canister itself, its location and connection method also play an important role.

In the vehicles, serial low-pressure fuel systems of are installed, in which separate technical solutions are implemented by NAMI [7, 8]. Due to the placement features, a unified arrangement of the carbon canister under the bottom of the car, in front of the fuel tank in the direction of movement, was chosen. The location of the carbon canister is shown in Figure 3.

![Figure 3. Location of the UMP carbon canister on the example of a sedan car. 1 - fuel tank; 2 - filling pipe with safety two-way valve; 3 - carbon canister.](image)

With this arrangement of the adsorber in the first stages of the project, the connection scheme of the carbon canister to the fuel tank was used, shown in Figure 4. With this connection scheme, common in many vehicles, the carbon canister is connected directly to the roll-over valves of the fuel tank. To purge the carbon canister in various operating modes of the V8 engine of the equipped with turbochargers, the purge line after the solenoid valve of the purge of the carbon canister is split and comes in one part to the throttle space, for the operation of the purge in modes where the turbocharger does not create sufficient boost pressure and in the line of the supply pipe with the second part, for modes when the boost pressure is sufficient to ensure the purge of the carbon canister. Initial tests have shown the efficiency of such a fuel tank ventilation scheme.

![Figure 4. Connection schematic of the carbon canister directly to the roll-over valve of the fuel tank. 1 - fuel tank; 2 - filling pipe with a two-way safety valve; 3 - carbon canister; 4 – roll-over valve; a - vapor line from the roll-over valve on the fuel tank to the carbon canister; b – vapor line connecting the carbon canister to the purge line; c - line of the air intake of the carbon canister; d - vapor line of the filling limiter.](image)
But during the tests in the vehicles at different driving modes and idling under different weather conditions, some shortcomings of such an carbon canister connection scheme were revealed. When conducting tests with a control liquid trap in the vapor line from the fuel tank to the carbon canister, the connection schematic is shown in Figure 5, when the vehicle is idling after driving in modes with sharp steering shifts at high speed, close to skidding, sharp accelerations and decelerations leading to significant splashes of fuel, with increasing pressure in the fuel tank as a result of an increase in fuel temperature, the appearance of liquid fuel in the liquid trap was revealed, which got into the line of the vapor line during sharp maneuvers through the roll-over valves and under the influence of excess pressure in the tank was moved towards the carbon canister. And also, in one of the most unfavorable conditions for the fuel tank ventilation system, during prolonged operation of the vehicle at idle, after significant heating of the fuel from the electric fuel pump (over 40 °C) at a much lower ambient temperature (+10 °C), increased condensation was observed, caused by a sharp decrease in the temperature of fuel vapors when leaving the fuel tank.

Figure 5. Connection schematic of the control liquid trap to the vapor line from the fuel tank to the carbon canister. 1 - fuel tank; 2 - filling pipe with a two-way safety valve; 3 – carbon canister; 4 – roll-over valve; 5-liquid trap in front of the carbon canister; a - vapor line from the roll-over valve on the fuel tank to the carbon canister; b – vapor line connecting the carbon canister to the purge line; c - line of the air intake of the carbon canister; d - vapor line of the filling limiter.

The constant ingress of an excessive amount of the liquid phase of the fuel into the carbon canister leads to a degradation of the working capacity of the activated carbon inside it and a significant decrease in the efficiency of the fuel vapor working system as a whole, and even the possible appearance of a fuel smell around the car when the carbon canister overflows. To determine the effect of the liquid phase of the fuel on the working capacity of the carbon canister, tests were carried out under laboratory conditions, in which the working capacity of two carbon canisters was compared after 9 saturation-purge cycles –a new adsorber and an adsorber pre-filled with fuel and purged for 8 hours. So it was found that after contact with liquid fuel, the working capacity of the carbon canister can decrease by 25% or more.

Due to the specificity of the fuel tank placement, the configuration of which does not allow the use of roll-over valves with an integrated liquid trap and to reduce the amount of condensed fuel vapors in the vapor line from the fuel tank to the carbon canister, a new connection scheme for the ventilation system was developed, shown in Figure 6. The new scheme involves the integration into a common line of the fuel tank ventilation lines of the filling limiter line during refueling and the tank ventilation line through roll-over valves, and the exit of fuel vapor into the carbon canister through the upper point in the filling pipe, as well as the introduction of a float valve of the filling limiter and a non-return valve of the flap type after the filling neck of the fuel tank, which eliminates the splash of fuel into the filling pipe and the outflow of fuel during the turn in through the carbon canister. The last two valves also had a positive effect on the refueling process, eliminating the injection of fuel into the upper part of the
filling pipe and its possible splash out, and as a result, the fuel entering the carbon canister during refueling.

Figure 6. Connection schematic of the carbon canister to the combined fuel tank ventilation line. 1 - fuel tank; 2 – filling pipe with a safety two – way valve; 3 – carbon canister; 4 – roll-over valve; 5 - float valve of the filling limiter; 6 – non–return valve of the flap type; a - line of the combined vapor line of the filling limiter and the roll-over valve from the fuel tank to the filling pipe; b – vapor line connecting the filling pipe to the carbon canister; c - vapor line connecting the carbon canister to the purge line; d - line of the air intake carbon canister.

This connection scheme made it possible to exclude the ingress of liquid fuel into the vapor line during active driving with a strong splashing of fuel in the tank. And also due to the fact that fuel vapors at a high temperature in the fuel tank are sent to the carbon canister through the volume of the filling pipe, which in the upper part has a temperature close to the ambient air temperature, and in the case of a significant temperature difference, some of the vapors have time to cool down and condense back into the tank, thereby preventing a significant amount of condensate from entering the carbon canister.

At the same time, the algorithms for the operation of the carbon canister purge valve were optimized, which made it possible to maintain the purge of the carbon canister in a very wide range of engine operating modes, including constantly maintaining it at idle. Also, to reduce the external thermal impact from the exhaust system, and as a result, reduce the evaporation of fuel from heating, heat-reflecting screens were optimized. These solutions made it possible to reduce the loading of the carbon canister with fuel vapors in the operating modes of the vehicle, in which the carbon canister is purged, and thereby increasing the efficiency of the fuel vapor control system in the modes when the purge is not performed, in particular, on a muffled vehicle. To reduce the load of the carbon canister, the introduction of a restrictor in the vapor line from the fuel tank to the carbon canister is also considered. The tests carried out helped to establish that reducing the cross-section of the vapor line at the exit from the filling pipe allows improving the quality of the carbon canister purge due to the increasing resistance of this line when purging the carbon canister and, as a result, less suction of fuel vapor from the tank during purging. The implementation of the control system for the electric fuel pump module is also being worked out, the effectiveness of reducing the thermal impact on the fuel inside the tank of which is also confirmed during bench tests.

Despite the improvements made, work continues on the modernization and implementation of new fuel tank ventilation schemes. This is due to the introduction of various solutions for hybrid vehicles and the tasks of entering new promising markets, the requirements for hydrocarbon emissions as a result of evaporation are being tightened every year. For example, in China, from 2020, more stringent requirements have been introduced, setting the same limit on emissions at 2 g, but including a 48-hour daily test and the mandatory presence of a fuel vapor control system during refueling. Also, when
driving hybrid vehicles without an internal combustion engine, purging the carbon canister is impossible and, accordingly, it is necessary to look for ways to limit the filling of the carbon canister. One of these options is the forced closure of the carbon canister from the fuel tank ventilation line by means of a normally closed electronically controlled valve. At the same time, most of the time, fuel vapors are isolated in the tank. The valve opens when refueling, when there are conditions for purging the carbon canister, or when the permissible pressure in the tank is exceeded, freeing the way for fuel vapors to enter the carbon canister. In this scheme, a pressure sensor must be provided in the design of the fuel tank.

Figure 7 shows a promising scheme of fuel tank ventilation, including a larger carbon canister located above the fuel tank and a different trace of the vapor line, which, when the valve for limiting the filling of the carbon canister is opened, removes fuel vapors during refueling into the carbon canister, preventing them from entering the atmosphere.

![Figure 7. Scheme of integration of the fuel vapor control system during refueling in the hybrid version of the UMP vehicle. 1 - fuel tank; 2 - filling pipe with a two-way safety valve; 3 – carbon canister; 4 – roll-over valve; 5-float valve of the filling limiter; 6 - valve for limiting the filling of the carbon canister; 7 - pressure sensor in the fuel tank; a - line of the combined vapor line of the filling limiter and the roll-over valve from the fuel tank to the carbon canister; b - vapor line connecting the carbon canister to the purge line; c - line of the air intake of the carbon canister.](image)

3. Conclusions
To ensure the protection of the environment from harmful emissions generated during the operation of vehicles with forced ignition of fuel, including as a result of fuel evaporation, restrictions on the regulation of these emissions are established at the international level. These restrictions are getting tougher every year.

Within the framework of the project, based on the calculations of the fuel evaporation volume and the research work carried out on the connection schemes of the carbon canister, a fuel tank ventilation system was developed to meet the standards adopted in Russia.

Various fuel tank ventilation schemes are calculated and worked out, which must meet the legal requirements of countries considered as promising markets.

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