The method of synthesis of new structural schemes of additional working equipment of the motor grader with the use of graphs and matrices

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Abstract. The paper considers a new approach to determining the external noise of road construction and earthmoving machines. The article shows that the existing method gives overestimated measurement results for earth moving vehicles. It was also revealed that due to the fact that the known methods for determining the external noise of road construction machines do not give a real picture of the external noise emitted by the machines, there are no devices for measuring the real noise of the vehicles. The authors provide the results of experimental studies performed at the plant of JSC "Bryansk Arsenal".

1. Introduction
Constantly increasing requirements for road construction and earthmoving machines (RCM and EM), especially in terms of their safety, ergonomics and environmental friendliness, also require the development of new, more advanced methods for determining the parameters of machines that affect these indicators.

One of the main parameters affecting labor safety is the level of external noise emitted by machines. The limit value of external noise affecting workers located in the working area is determined by GOST 12.1.003-83 and is equal to 80 dBA based on an 8-hour working day.

The World Health Organization estimates that the noise level at which the risk of hearing damage is minimal is 75 dBA at an 8-hour working day.

Since July 1, 1995, the Russian Federation introduced mandatory certification of road construction and earthmoving machinery, which should check the level of external noise.

The methods for determining external noise according to GOST 27717-88 and GOST 28975-91 suggest measuring external noise when simulating working movements or operating the machine at maximum speed and only on a spherical measuring surface where noise sensors are located, which does not provide reliable data on external noise of the machine.
The existing methods for determining the external noise of road construction and earthmoving machinery do not imply the possibility of changing the external noise emission by the machine during operation and do not take into account the accumulation of the effect of noise on workers in the working area with unstable operating mode and location of the machine. Moreover, they can’t identify the areas around the entire trajectory of the machine, where external noise is maximum.

Inaccuracies in the methods for determining the external noise emitted by road construction and earthmoving machinery can lead either to the danger of harmful effects on the human body or to unreasonably high material costs for noise reduction.

Therefore, there is a need to develop a methodology that allows to increase the accuracy of determining the external noise emitted by road construction and earthmoving machinery, which provides an objective assessment of machines taking into account the technology of work.

In relation to road construction and earthmoving machinery the Russian Federation applies GOST 27717-88, GOST 28975-91 and RD 22-219-88. There are also standards ISO 4872, 1585, 7216, 6393, 4871 as well as national standards SAE J1805, J1174, J1372, J88, J1262, J1008 VDI 3749 and others, which practically repeat the well-known ISO standards. All known techniques involve the use of measuring surfaces in the form of a hemisphere or parallelepiped.

As a result of the analysis of existing methods for determining the external noise of road construction and earthmoving machinery, we drew some conclusions.

1. The use of hemispherical measuring surfaces and measuring surfaces in the form of a parallelepiped does not allow us to determine the external noise of the road construction and earthmoving machinery, since there is no way to surround the entire trajectory of the movement of cyclic machines during operation, and obviously the entire trajectory of the movement of a machine with continuous working movement.

2. Measurement of external noise only at maximum engine speeds without taking into account the external real load on the working body leads to distorted results for measuring external noise of the road construction and earthmoving machinery.

3. Among the existing methods for determining noise, only the SAE J1166 standard proposes the complete elements of the duty cycle for cyclic machines and the conditions for performing work for continuous machines.

4. Known methods for determining the external noise of road construction and earthmoving machinery do not give a real picture of the external noise emitted by the machines.

5. The development of new, more accurate methods is possible based on the analysis of real work processes performed by machines.

The aim of the work is to develop a methodology that would improve the accuracy of determining the external noise emitted by road construction and earthmoving machinery and which could provide an objective assessment of machines taking into account the technology of the work performed.

2. Analytical model

All road construction and earthmoving machines with continuous working movements can be divided into two groups:

- machines having a low working speed, which the working area allows the personnel to be there all the time, for example, pavers, road construction materials spreaders;
- machines having a working speed that does not allow personnel to be in the working area, for example, motor graders, wheeled bulldozers (when paving paths and roads).

The working cycle time of a machine performing cyclic working movements can be determined by the formula:

\[ T_c = T_{px} + T_{xx} + T_{oct} \]  \hspace{1cm} (1)

where: \( T_{px} \) – time of operating run; \( T_{xx} \) – time of blank run; \( T_{oct} \) – time of stops at the beginning of blank and operating run. The working cycle time can also be determined by another formula:
\[ T_c = \frac{S_p}{V_p} + \frac{S_{xx}}{V_{xx}} + T_{stp}, \]  

(2)

where: \( S_p, S_{xx} \) – lengths of blank and operating run; \( V_p, V_{xx} \) – velocities of blank and operating run.

Formula (1) can be presented in expanded form for various machines. For example, for loaders:

\[ T_c = 4 \times T_{pp} + T_n + T_p + T_m + T_g + T_x, \]  

(3)

where: \( T_{pp} \) – gear shift duration; \( T_n \) – loading duration; \( T_p \) – unloading duration; \( T_m \) – loader maneuvering duration; \( T_g, T_x \) – duration of cargo transportation and blank run. Similar formulas can be obtained for other machines with cyclic working movements. During working and idling, stops at the beginning of blank and operating runs, the operating modes of the machine can be different and therefore the levels of noise emitted by the machine will also be different.

As a result of a theoretical analysis of noise emission of road construction and earthmoving machinery with cyclic working movement, it was obtained that the emitted noise consists of:

- noise emitted by the machine before performing the duty cycle when shifting gears - \( L_1 \);
- noise emitted by the machine when making the operating run - \( L_2 \);
- noise emitted by the machine before performing blank run when shifting gears and turning on the reverse - \( L_3 \);
- noise emitted by the machine when making the blank run - \( L_4 \).

When performing the duty cycle with a bulldozer (Figure 1), we determined the equivalent noise level at the control point. It was assumed that the control point at which it is necessary to determine the equivalent noise level is located on the longitudinal axis of the bulldozer and the axis of the direction of movement. The distance from the control point to the center of the bulldozer at the beginning of the cycle is \( R_0 \).

\[ L_i = L_0 - 20 \times \log \frac{R_i}{R_0}, \]  

(4)

where \( L_0 \) – noise level at the control point at the beginning of the operating run.

The current distance value is determined by the formula:

\[ R_i = R_0 + V_{px} \times T_{px}, \]  

(5)

![Figure 1.](image-url)
where: $V_{px}$ – the current speed of the bulldozer when performing the operating run; $T_{px}$ - the current time of the operating run.

The equivalent noise level for the entire operating run is determined as the average noise level according to the formula:

$$L_{ekb} = 10 \times \lg \left[ \frac{1}{T_4} \int_0^{T_4} 10^{0.1 \cdot L_{t}(t)} dt \right],$$  \hspace{1cm} (6)

The noise level at time $t$ is determined by the formula:

$$L_t = L_{0px} - 20 \times \lg \frac{R(i)}{R_0},$$  \hspace{1cm} (7)

where: $L_{0px}$ – noise level when the bulldozer is at point 1 (Figure 1); $R_0$ – distance from measuring point to point 1; $R(i)$ – current distance from the measuring point to the moving bulldozer.

Final formula (6) has the form:

$$L_{ekb2} = L_{0px} - 10 \times \lg \frac{S+R_0}{R_0}$$  \hspace{1cm} (8)

where $S = V_{px} \times T_2$.

When performing the blank (reverse) run of the bulldozer, the distance $R$ will be determined by the formula:

$$R = S - V_{xx} \times t_{xx} + R_0,$$  \hspace{1cm} (9)

where: $t_{xx}$ – current time of the blank run; $S$ – length of blank run equal to the operating time.

The equivalent noise level of a bulldozer when idling for time $T$ is determined by the formula:

$$L_{ekb4} = L_{0xx} + 10 \times \lg \left[ \frac{R_0^2}{V_{xx}^2 \cdot T_4} \cdot \left( \frac{1}{S-V_{xx} \cdot T_4+R_0} - \frac{1}{S+R_0} \right) \right],$$ \hspace{1cm} (10)

Accordingly, for the current moment

$$L_{ekb4} = L_{0xx} - 10 \times \lg \frac{(S-V_{xx} \cdot t_{xx}+R_0)+(S+R_0)}{R_0^2}$$  \hspace{1cm} (11)

where $L_{0xx}$ – the noise level at the control point when the bulldozer is at the near point at the blank run. The equivalent noise level for a full cycle covers four operating modes and is determined by the formula

$$L_{ekb} = 10 \times \lg \frac{\sum_{i=1}^{4} T_i \cdot 10^{0.1 \cdot L_{0xx}}}{\sum_{i=1}^{4} T_i}$$  \hspace{1cm} (12)

Considering the noise emission of a bulldozer only when it is working and idling, the formula for determining the equivalent noise level for the operating run at the current time $t_{xx}$ has the form:

$$L_{ekb2}(t_{px}) = L_{0px} + 10 \times \lg \left[ \frac{R_0^2}{V_{xx} \cdot t_{px}} \cdot \left( \frac{1}{R_0} - \frac{1}{V_{px} \cdot t_{px}+R_0} \right) \right].$$  \hspace{1cm} (13)

At the current moment of time at the blank run:

$$L_{ekb}(t_{xx}) = 10 \times \lg \frac{T_2 \cdot 10^{0.1 \cdot L_{ekb2}(T_2)} \cdot t_{xx} \cdot 10^{0.1 \cdot L_{ekb4}(t_{xx})}}{T_2 \cdot t_{xx}}.$$  \hspace{1cm} (14)

where: $L_{ekb2}$ – equivalent noise level over the entire operating run, i.e. during $T_2$; $L_{ekb4}$ – equivalent noise level at the current time $t_{xx}$ of the blank run, defined as

$$L_{ekb4}(t_{xx}) = L_{ekb}(t_{xx}) = 10 \times \lg \frac{T_2 \cdot 10^{0.1 \cdot L_{ekb2}(T_2)} \cdot t_{xx} \cdot 10^{0.1 \cdot L_{ekb4}(t_{xx})}}{T_2 \cdot t_{xx}}.$$  \hspace{1cm} (15)

when the loader performed the operation (Figure 2), it was obtained that when the loader moves from point 1 to point 2, the equivalent level of external noise during this movement is determined by the formula:

$$L_{ekb1-2}(t) = L_0 + 10 \times \lg \left[ \frac{R_0^2}{V_{xx} \cdot t \cdot \sin \alpha} \cdot \left( \arctg \frac{V \cdot t + R_0 \cdot \cos \alpha}{R_0 \cdot \sin \alpha} + L_{ekb1-2}(t) \right) \right] = I,$$  \hspace{1cm} (16)
Figure 2. Loader duty cycle scheme. O, O’ - control points; 1 - the start point of the operating run; 2 - loading point; t. 3 - point of discharge.

When moving from point 2 to point 1 (when performing a reverse run), the equivalent level of external noise of the loader during this movement is determined by the formula:

$$L_{ekb1-2}(t) = L_0 + 10 \times \log \left[ \frac{R_0}{V \times t \times \sin \alpha} \left( \arctg \frac{V \times t - S - R_0 \times \cos \alpha}{R_0 \times \sin \alpha} + \arctg \frac{S - R_0 \times \cos \alpha}{R_0 \times \sin \alpha} \right) \right],$$  \hspace{1cm} (17)

As shown by preliminary tests of road construction and earthmoving machinery with continuous working movement, machines having a low working speed and which working area allows personnel to be there constantly, emit different noise in different directions within the working area at the same distance from the machine. Therefore, the equivalent noise level affecting an employee can be determined by the formula:

$$L_{ekb} = 10 \times \log \left[ \frac{1}{\sum T_i} \times \left( \sum T_i \times 10^{0.1 \times L_{0i}} \right) \right],$$  \hspace{1cm} (18)

where: $L_{0i}$ - values of the equivalent noise level acting on an employee located at the i-th point, during his stay at the i-th point; $T_i$ - time spent by the employee at the i-th point of his working area.

As a result of the analysis of theoretical dependencies, we found that existing methods overestimate the level of external noise affecting a motionlessly located object, which depends on the distance of movement of road construction and earthmoving machinery with cyclic working movement, less than 6 dBA or more on the level of external noise, determined by existing methods. The expected value of the level of external noise of road construction and earthmoving machinery, having continuous working movement, also differs from the level of external noise determined by existing known methods.
3. Experiment, results and conclusions

For experimental determination of external noise, we used both standard methods, described in current GOST 28975-91, and the newly developed method, protected by a patent for the invention according to application No. 95121519/03. According to the new method of measuring external noise emitted by road construction machines, a measuring surface with noise sensors located on it surrounds the entire working trajectory of the cyclic movement of the machine. One of the tested machines was the DZ-198 motor grader manufactured by “Bryansk Arsenal” JSC.

Figure 3. Motor grader DZ-198 produced by JSC "Bryansk Arsenal" at operation during testing.

Some calculation results and experimental data of external noise levels for the 1840 mini loader manufactured by Case are shown in Table 1 and shown in Figures 4, 5, 6. As a result of preliminary measurements, we found that the background noise was 51 dBa, and the noise level of the mini-loader, measured at a distance of 4 m from the machine at the beginning of the working cycle, was \( L_o = 79 \) dBA, and the average speed of the mini-loader during its duty cycle was 5 km / h.

Table 1. Theoretical and experimental data on the level of external noise for a mini-loader 1840 manufactured by Case Initial data: \( L_o = 79 \) dBA, \( S = 10 \) m, \( R_0 = 4 \) m, \( V = 5 \) km / h, \( \alpha = 30^\circ \).

| Time, [sec] | Theoretical data, [dBA] | Experimental data, [dBA] | Data discrepancy, [dBA] | From point to point |
|-------------|-------------------------|--------------------------|-------------------------|---------------------|
| 0,0         | 79,00                   | 79,0                     | 0,00                    | 1 to 2              |
| 0,6         | 78,13                   |                          |                         | 1 to 2              |
| 1,2         | 77,39                   |                          |                         | 1 to 2              |
| 1,8         | 76,75                   |                          |                         | 1 to 2              |
| 2,4         | 76,19                   |                          |                         | 1 to 2              |
| 3,0         | 75,69                   | 75,6                     | 0,09                    | 1 to 2              |
| 3,6         | 75,24                   |                          |                         | 1 to 2              |
| 4,2         | 74,83                   |                          |                         | 1 to 2              |
| 4,8         | 74,45                   |                          |                         | 1 to 2              |
| 5,4         | 74,11                   |                          |                         | 1 to 2              |
| 6,0         | 73,78                   | 73,8                     | 0,02                    | 1 to 2              |
| 6,6         | 73,50                   |                          |                         | 2 to 1              |
| 7,2         | 73,27                   |                          |                         | 2 to 1              |
| 7,8         | 73,10                   |                          |                         | 2 to 1              |
| 8,4         | 72,97                   |                          |                         | 2 to 1              |
| 9,0         | 72,90                   | 72,7                     | 0,20                    | 2 to 1              |
| 9,6         | 72,90                   |                          |                         | 2 to 1              |
Let’s look at the graphs of the theoretical and experimental equivalent noise levels according to the data in Table 1.

| Time, [sec] | Theoretical data, [dBA] | Experimental data, [dBA] | Data discrepancy, [dBA] | From point to point |
|-------------|--------------------------|--------------------------|------------------------|---------------------|
| 10.2        | 72.96                    |                          |                        | 2 to 1              |
| 10.8        | 73.11                    |                          |                        | 2 to 1              |
| 11.4        | 73.37                    |                          |                        | 2 to 1              |
| 12.0        | 73.78                    | 74.2                     | 0.42                   | 2 to 1              |
| 12.6        | 74.13                    |                          |                        | 1 to 3              |
| 13.2        | 74.27                    |                          |                        | 1 to 3              |
| 13.8        | 74.31                    |                          |                        | 1 to 3              |
| 14.4        | 74.29                    |                          |                        | 1 to 3              |
| 15.0        | 74.24                    | 74.8                     | 0.56                   | 1 to 3              |
| 15.6        | 74.17                    |                          |                        | 1 to 3              |
| 16.2        | 74.08                    |                          |                        | 1 to 3              |
| 16.8        | 73.99                    |                          |                        | 1 to 3              |
| 17.4        | 73.89                    |                          |                        | 1 to 3              |
| 18.0        | 73.78                    | 74.2                     | 0.42                   | 1 to 3              |
| 18.6        | 73.69                    |                          |                        | 3 to 1              |
| 19.2        | 73.60                    |                          |                        | 3 to 1              |
| 19.8        | 73.53                    |                          |                        | 3 to 1              |
| 20.4        | 73.47                    |                          |                        | 3 to 1              |
| 21.0        | 73.43                    | 72.8                     | 0.63                   | 3 to 1              |
| 21.6        | 73.41                    |                          |                        | 3 to 1              |
| 22.2        | 73.42                    |                          |                        | 3 to 1              |
| 22.8        | 73.48                    |                          |                        | 3 to 1              |
| 23.4        | 73.59                    |                          |                        | 3 to 1              |
| 24.0        | 73.78                    | 74.2                     | 0.42                   | 3 to 1              |

Max. discrepancy 0.63
Figure 4. Graphs of theoretical and experimental noise levels for Case 1840 mini-loader.

Table 2. Initial data: $L_0 = 79$ dBA, $L'_0 = 79,29$ dBA, $S = 10$ m, $R_0 = 4$ m, $R'_0 = 8,66$ m, $V = 5$ km/h, $\alpha = 150^\circ$. The control point is located between the loading and unloading points.

| Time, [sec] | Theoretical data, [dBA] | Experimental data, [dBA] | Data discrepancy, [dBA] | From point to point |
|-------------|-------------------------|-------------------------|------------------------|--------------------|
| 0,0         | 72,29                   | 72,3                    | 0,01                   | 1 to 2             |
| 0,6         | 72,74                   | 72,3                    |                        | 1 to 2             |
| 1,2         | 73,23                   | 73,75                   |                        | 1 to 2             |
| 1,8         | 73,75                   | 74,31                   |                        | 1 to 2             |
| 2,4         | 74,88                   | 74,4                    | 0,48                   | 1 to 2             |
| 3,0         | 75,43                   | 75,92                   |                        | 1 to 2             |
| 3,6         | 76,30                   | 76,53                   |                        | 1 to 2             |
| 4,2         | 76,64                   | 76,0                    | 0,64                   | 1 to 2             |
| 4,8         | 76,72                   | 76,85                   |                        | 2 to 1             |
| 5,4         | 77,07                   | 76,98                   |                        | 2 to 1             |
| 6,0         | 77,10                   | 77,5                    | 0,40                   | 2 to 1             |
| 6,6         | 77,77                   | 77,07                   |                        | 2 to 1             |
| 7,2         | 76,99                   | 76,89                   |                        | 2 to 1             |
| 7,8         | 76,77                   |                         |                        |                    |
| 8,4         | 76,64                   |                         |                        |                    |
| 9,0         | 76,64                   |                         |                        |                    |
| 9,6         | 76,64                   |                         |                        |                    |
| 10,2        | 76,64                   |                         |                        |                    |
| 10,8        | 76,64                   |                         |                        |                    |
| 11,4        | 76,64                   |                         |                        |                    |
| 12,0        | 76,64                   |                         |                        |                    |

Max. discrepancy Blank run 0,64 2 to 1
| Time, [sec] | Theoretical data, [dBA] | Experimental data, [dBA] | Data discrepancy, [dBA] | From point to point |
|------------|------------------------|-------------------------|------------------------|---------------------|
| 0,0        | 77,06                  | 77,1                    | 0,04                   | 2 to 1              |
| 0,6        | 77,47                  |                         |                        | 2 to 1              |
| 1,2        | 77,78                  |                         |                        | 2 to 1              |
| 1,8        | 77,96                  |                         |                        | 2 to 1              |
| 2,4        | 77,99                  |                         |                        | 2 to 1              |
| 3,0        | 77,89                  | 77,9                    | 0,01                   | 2 to 1              |
| 3,6        | 77,70                  |                         |                        | 2 to 1              |
| 4,2        | 77,46                  |                         |                        | 2 to 1              |
| 4,8        | 77,19                  |                         |                        | 2 to 1              |
| 5,4        | 76,91                  |                         |                        | 2 to 1              |
| 6,0        | 76,64                  | 77,5                    | 0,86                   | 2 to 1              |
| Max.       |                        |                         |                        | 0,86                |

The graphs reflecting the data in Table 2 are presented below.

**Figure 5.** Graph of theoretical and experimental noise levels of the 1840 mini-loader for a full cycle (control point between the loading and unloading points).

**Figure 6.** Schedule of theoretical and experimental noise levels of the 1840 mini-loader per blank run (reference point between the loading and unloading points).

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