Optimization of the harvesting and transport complex work in forage conservation

G A Iovlev*, M K Sahakyan, A G Nesgovorov, A A Sadov and I I Goldina

Ural State Agrarian University, 620075, Ekaterinburg, K-Liebknecht st., 42, Yekaterinburg, Russia

* E-mail: gri iovlev@yandex.ru

Abstract. The need to use high-performance machinery in agriculture is caused by a number of reasons. The main of them is the development of scientific and technological progress, both in the economy as a whole and in the agricultural sector. This is aimed at increasing labor productivity, reducing costs, and improving production efficiency. All of this is relevant due to a decrease in the number of agricultural machinery working in agricultural production, a decrease in the area of arable land and the area of sowings of specific crops, including forage crops. Of the entire production process of forage conservation, the most important is harvesting. The quality of harvested forage directly depends on the calendar terms of harvesting, duration. With the appearance and use of high-performance forage harvesters of domestic and foreign production in forage harvesting technologies, there was an objective need to create harvesting and transport complexes (HTC). For the effective HTC operation, information is needed on the optimal combination of the number of forage harvesters, vehicles, equipment for leveling and "ramming" the green mass in the silo trench.

1. Introduction

Animal husbandry, as a branch of agriculture, is of great importance for providing food to the population of states. Even if we take the agricultural production of the middle zone of Russia, the Urals, Siberia, then animal husbandry gives the following products used as food and raw materials for processing: milk, meat, wool, woofells, horns for the production of medicines, etc. Dairy products, cheeses, baby food, sausages, smoked meats, clothes, shoes, etc. are prepared from animal products. Food products of animal origin in physical weight account for 57.8% of the total volume (in Kazakhstan – 50.6%) [1].

To provide the population with food of animal origin, Russia contains a certain number of dairy herds, herds of meat directions, with a certain productivity (milk yield per 1 feed cow, average daily weight gain). To provide livestock with feed, certain areas are needed for the production of feed, a set of agricultural machinery. The dynamics of changes in the number of cattle, productivity, availability of areas for fodder crops, availability of equipment used in forage harvesting is presented in Table 1.

Table 1. Livestock of cattle, productivity, availability of areas for fodder crops, availability of equipment used in forage harvesting [2-4].

| Indicators | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|-----------|------|------|------|------|------|------|------|------|------|------|
| Years     |      |      |      |      |      |      |      |      |      |      |
From the data presented in Table 1, the number of cattle and cows decreased by 9.3% and 10.4%, respectively, but productivity during this period increased by 55.2% in milk yield and by 28% in average daily weight gain. The area under forage crops (annual grasses, perennial, corn for silage, cornage) decreased by 20.3%. The first conclusion that can be drawn from the data from Table 1 is that the increase in livestock productivity has become possible because of the higher-quality feed conservation, the use of more productive breeds and the use of more efficient modern technologies for the preparation and distribution of fodder, keeping and milking of cows.

It should be noted that the availability of tractors used in forage conservation, forage harvesters decreased by 1.87 times and 2.33 times, respectively. As a result of the reduction in the number of agricultural machinery, cars used in forage conservation, there is a need for more efficient use of this equipment during forage conservation. Effective use consists in determining the optimal composition of the harvesting and transport complex (HTC), which allows for the procurement of high-quality feed in the optimal time with the least cost.

### 2. Materials and Methods

The research was carried out based on agricultural organizations of the Sverdlovsk region - JSC "Kamenskoye", by the teachers of the department "Service of transport and technological machines".

| Livestock of cattle, million heads | 19.9 | 19.68 | 19.27 | 18.92 | 18.62 | 18.35 | 18.29 | 18.15 | 18.13 | 18.05 |
|-----------------------------------|------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Cow population, million heads     | 8.81 | 8.66  | 8.43  | 8.26  | 8.11  | 7.97  | 7.95  | 7.94  | 7.97  | 7.89  |
| Milk yield per 1 cow, kg          | 4732 | 4985  | 5001  | 5371  | 5699  | 5908  | 6272  | 6524  | 6925  | 7343  |
| Average daily weight gain, g      | 514  | 526   | 520   | 5371  | 5699  | 5908  | 6272  | 6524  | 6925  | 7343  |
| Areas under forage crops, million hectares | 18.08 | 17.46 | 17.18 | 17.09 | 16.95 | 15.14 | 16.31 | 16.24 | 15.57 | 14.41 |
| Number of tractors used in fodder conservation, thousand pcs.* | 77.99 | 71.49 | 64.72 | 61.07 | 56.65 | 47.98 | 49.68 | 48.77 | 45.15 | 41.78 |
| Availability of forage harvesters, thousand pcs. | 18.91 | 17.59 | 16.13 | 15.16 | 14.04 | 13.26 | 12.68 | 12.25 | 11.77 | 8.12  |

* The indicator "Number of tractors used in forage conservation" is calculated by the author based on the availability of tractors in agricultural organizations, areas under forage crops, availability of agricultural machinery.
and equipment in the Agro-Industrial Complex" of the FSBEI HE Ural SAU and students of the training direction "Operation of transport and technological machines and complexes" - members of the Student Scientific Society (SSS).

In one case, studies were carried out on haylage harvesting from annual and perennial grasses (alfalfa), in the other, on silage harvesting from corn. In both cases, statistical data were taken during the work of two detachments consisting of forage harvesters and vehicles.

The following agricultural machinery was used in the technology of haylage conservation:

1. Grass mowing - tractor Belarus 1221 + mower Kuhn 303, tractor Case Puma 210 + mower Kuhn 883.
2. Roll formation, tilling - tractor Belarus 82.1 + swath maker Kuhn 7932.
3. Selection and swath grinding - Jaguar 830 (850) with PICK UP 300 (380).
4. Transportation - KAMAZ - 55102 + trailer SZAP 8551 (8527), trailer NEFAZ - 8560, Tractors ATM - 5280, T-150K (HTZ-150K) + trailer 3PTS-12, Belarus 1221 + trailer 1PTS-9, Belarus 82.1 + trailer 2PTS-6.

In the technology of silage conservation from corn:

1. Mowing and grinding - Jaguar 830 (850) with header ORBIS 450 (600 SD).
2. Transportation – vehicles similar to haylage conservation technology.

The technology of cornage conservation uses a Jaguar 830 (850) forage harvester with a header for harvesting corn for grain and a special spacer for connecting the Kaiman (Domioni) header with a combine harvester.

The fundamental difference between the technology of haylage conservation and the technology of corn silage conservation is that the mown mass from several passes is formed into a roll, the formed roll is subjected to agitation several times to achieve the necessary humidity, depending on the mass and humidity of the swath. Then the swath selection and grinding are carried out.

To optimize the work of the harvesting and transport complex for forage conservation, studies were conducted on the work of four detachments: two detachments for haylage conservation from annual and perennial grasses; two detachments for silage conservation from corn. The detachments worked at different departments on different calendar dates.

The composition of the detachments for haylage conservation.

I detachment:
- Jaguar 830, Jaguar 850 forage harvesters – 2 units;
- vehicles: KAMAZ - 55102 with trailer – 2 units; Belarus 82.1 with trailer 2PTS-6, Belarus 82.1 with trailer 1PTS-9 - 2 units.

II detachment:
- Jaguar 850 forage harvester – 1 unit;
- vehicles: KAMAZ - 55102 with trailer – 1 unit; Belarus 82.1 with trailer 2PTS-6, Belarus 82.1 with trailer 1PTS-9 - 2 units.

The composition of the detachments for corn silage conservation.

I detachment:
- Jaguar 850 forage harvesters – 2 units;
- vehicles: KAMAZ - 55102 with a trailer – 6 units; ATM – 5280 tractor with a 3PTS-12 trailer, T-150K with a 3PTS-12 trailer, Belarus 1221 with a 1PTS-9 trailer.

II detachment:
- Jaguar 830 forage harvester – 1 unit;
- vehicles: Belarus 1221 with trailer 1PTS-9, Belarus 82.1 with trailer 2PTS-6 - 4 units.

The following methods were used in the study: classical mathematics, observation, comparison, measurement, experiment.

3. Results and Discussion

For research on optimizing the work of the HTC, measurements of the following statistical indicators were carried out.
On the work of forage harvesters:
- vehicle loading time;
- Vehicle waiting time for loading.
On the operation of vehicles:
- waiting time for loading;
- vehicle loading time;
- transport cycle time (by transport cycle we take the travel time to the silo trench, unloading time, travel time from the silo trench to the field).

In our study, we will present calculations for optimizing the work of the HTC on silage conservation from corn during the work of the first harvesting detachment. The results of calculations of the work of other detachments will be presented in tabular material and in the form of figures. Data on the operation of forage harvesters will be presented in Tables 2, 3.

Table 2. Information about the work of forage harvesters of the I detachment.

| No. | Jaguar 850 (header 6 m) | Jaguar 850 (header 4.5 m) |
|-----|-------------------------|---------------------------|
|     | Vehicle loading time, min. | Vehicle waiting time, min. | Vehicle loading time, min. | Vehicle waiting time, min. |
| 1   | 17 | 1 | 20 | - |
| 2   | 11 | 3 | 24 | - |
| 3   | 20 | 26 | 20 | 23 |
| 4   | 18 | 21 | 34 | 17 |
| 5   | 29 | 1 | 38 | - |
| 6   | 20 | 2 | 29 | - |
| 7   | 20 | - | 18 | - |
| 8   | 24 | - | 26 | - |
| 9   | 23 | - | 30 | - |
| 10  | 31 | 1 | 39 | - |
| 11  | 22 | - | 32 | - |
| 12  | 22 | 6 |   |   |
| 13  | 27 | 3 |   |   |
| 14  | 21 | - |   |   |

Table 3. Information about the work of forage harvester of the II detachment.

| No. | Vehicle loading time, min. | Vehicle waiting time, min. | No. | Vehicle loading time, min. | Vehicle waiting time, min. |
|-----|---------------------------|---------------------------|-----|---------------------------|---------------------------|
| 1   | 8 | 4 | 17 | 16 | - |
| 2   | 8 | 9 | 18 | 6 | - |
| 3   | 9 | - | 19 | 9 | - |
| 4   | 18 | 19 | 20 | 10 | - |
| 5   | 9 | 4 | 21 | 10 | - |
| 6   | 9 | - | 22 | 12 | 13 |
| 7   | 9 | - | 23 | 10 | - |
| 8   | 8 | 2 | 24 | 8 | - |
| 9   | 7 | - | 25 | 10 | - |
| 10  | 8 | - | 26 | 8 | - |
| 11  | 7 | 4 | 27 | 9 | - |
| 12  | 9 | 5 | 28 | 9 | - |
| 13  | 10 | - | 29 | 8 | - |
| 14  | 7 | - | 30 | 11 | - |
After processing the results, we will build graphs, having previously determined the laws of distribution of random variables. We will present the graphs in Figures 1-4.

![Figure 1. Vehicle loading time by fodder harvester Jaguar 850 with ORBIS 600 SD header.](image1)

The loading time of the vehicle by forage harvester (Figure 1) obeys the law of normal distribution, the waiting time of the vehicle (Figure 2) - the law of exponential distribution.

To clarify the distribution laws, we introduce numerical characteristics of a random variable.

![Figure 2. Waiting time for vehicle by fodder harvester Jaguar 850 with ORBIS 600 SD header.](image2)

I. Vehicle loading time with Jaguar 850 forage harvester with ORBIS 600 SD header.
Mathematical expectation.

\[ M(X) = x_1 \times p_1 + x_2 \times p_2 + \ldots + x_n \times p_n = 12 \times 0.07 + 18 \times 0.14 + 20 \times 0.22 + 22 \times 0.22 + 24 \times 0.14 + 28 \times 0.07 + 30 \times 0.07 + 32 \times 0.07 = 0.84 + 2.52 + 4.4 + 3.36 + 2.1 + 2.24 = 22 \text{ min.} \]

Variance.

\[ D(X) = (x_1 - m)^2 \times p_1 + (x_2 - m)^2 \times p_2 + \ldots + (x_n - m)^2 \times p_n \]

\[ m = M(X) = 12 \times 0.07 + 18 \times 0.14 + 20 \times 0.22 + 22 \times 0.22 + 24 \times 0.14 + 28 \times 0.07 + 30 \times 0.07 + 32 \times 0.07 = 0.84 + 2.52 + 4.4 + 3.36 + 2.1 + 2.24 = 22 \text{ min}^2 \]

Mean square deviation.

\[ \sigma = \sqrt{D(X)} = \sqrt{24.68} = 5.0 \text{ min.} \]

II. Vehicle waiting time.

\[ M(X) = 3 \times 0.36 + 6 \times 0.07 + 21 \times 0.07 + 27 \times 0.07 = 1.08 + 0.42 + 1.47 + 1.89 = 4.9 \text{ min.} \]

\[ D(X) = (0 - 4.9)^2 \times 0.36 + (3 - 4.9)^2 \times 0.07 + (6 - 4.9)^2 \times 0.07 + (21 - 4.9)^2 \times 0.07 + (27 - 4.9)^2 \times 0.07 = 8.64 + 0.25 + 0.08 + 18.14 + 34.19 = 61.3 \text{ min}^2 \]

\[ \sigma = \sqrt{D(X)} = \sqrt{61.3} = 7.8 \text{ min.} \]

III. Vehicle loading time with Jaguar 850 forage harvester with ORBIS 850 SD header.

Mathematical expectation.

\[ M(X) = 18 \times 0.09 + 20 \times 0.18 + 24 \times 0.09 + 26 \times 0.09 + 30 \times 0.19 + 32 \times 0.09 + 34 \times 0.09 + 38 \times 0.09 + 40 \times 0.09 = 1.62 + 3.6 + 2.16 + 2.34 + 5.7 + 2.88 + 3.42 + 3.6 = 28 \text{ min.} \]

Variance.

\[ D(X) = (18 - 28)^2 \times 0.09 + (20 - 28)^2 \times 0.18 + (24 - 28)^2 \times 0.09 + (26 - 28)^2 \times 0.09 + (30 - 28)^2 \times 0.19 + (32 - 28)^2 \times 0.09 + (34 - 28)^2 \times 0.09 + (38 - 28)^2 \times 0.09 + (40 - 28)^2 \times 0.09 = 9 + 11.52 + 0.08 + 0.36 + 0.76 + 3.24 + 9 + 12.96 = 48.28 \text{ min}^2 \]

Mean square deviation.

\[ \sigma = \sqrt{D(X)} = \sqrt{48.28} = 6.95 \text{ min.} \]

IV. Vehicle waiting time.

\[ M(X) = 18 \times 0.09 + 24 \times 0.09 = 1.62 + 2.16 = 3.78 \text{ min.} \]

\[ D(X) = (0 - 3.78)^2 \times 0.82 + (18 - 3.78)^2 \times 0.09 + (24 - 3.78)^2 \times 0.09 = 11.72 + 18.2 + 36.8 = 61.3 \text{ min}^2 \]

\[ \sigma = \sqrt{D(X)} = \sqrt{61.3} = 8.2 \text{ min.} \]

Figure 3. Vehicle loading time by fodder harvester Jaguar 830.
Figure 4. Waiting time for vehicle by fodder harvester Jaguar 830.

The vehicle loading time with the Jaguar 830 forage harvester (Figure 3) obeys the law of normal distribution with positive asymmetry, the waiting time of the vehicle (Figure 4) - the law of exponential distribution.

We clarify the laws of distribution.

I. The vehicle loading time with the Jaguar 830 forage harvester.

**Mathematical expectation.**

\[
M(X) = 6 	imes 0.03 + 7 	imes 0.09 + 8 	imes 0.28 + 9 	imes 0.29 + 10 	imes 0.16 + 11 	imes 0.03 + 12 	imes 0.06 + 16 	imes 0.03 + 18 	imes 0.03 = 9 \text{ min.}
\]

**Variance.**

\[
D(X) = (6-9)^2 	imes 0.03 + (7-9)^2 	imes 0.09 + (8-9)^2 	imes 0.28 + (9-9)^2 	imes 0.29 + (10-9)^2 	imes 0.16 + (11-9)^2 	imes 0.03 + (12-9)^2 	imes 0.06 + (16-9)^2 	imes 0.03 + (18-9)^2 	imes 0.03 = 5.63 \text{ min}^2
\]

**Mean square deviation.**

\[
\sigma = \sqrt{D(X)} = \sqrt{5.63} = 2.37 \text{ min.}
\]

II. Vehicle waiting time.

**Mathematical expectation.**

\[
M(X) = 2 	imes 0.03 + 4 	imes 0.12 + 6 	imes 0.03 + 10 	imes 0.03 + 14 	imes 0.03 + 20 	imes 0.03 = 2.28 \text{ min.}
\]

**Variance.**

\[
D(X) = (0-2.28)^2 	imes 0.73 + (2-2.28)^2 	imes 0.03 + (4-2.28)^2 	imes 0.12 + (6-2.28)^2 	imes 0.03 + (10-2.28)^2 	imes 0.03 + (14-2.28)^2 	imes 0.03 + (20-2.28)^2 	imes 0.03 = 0.18 + 0.63 + 2.24 + 2.61 + 1.6 + 0.33 + 0.72 + 0.48 + 0.54 = 9 \text{ min.}
\]

**Mean square deviation.**

\[
\sigma = \sqrt{D(X)} = \sqrt{9} = 3 \text{ min.}
\]

Data on the operation of transport will be presented in Table 4.

Table 4. Information about the operation of transport.

| Run number | I detachment | II detachment |
|------------|--------------|---------------|
| Loading waiting time, min | Loading waiting time, min | Loading waiting time, min |
| 1 | 7 | 17 | 1 | 4 | 17 |
| 2 | 30 | 18 | 2 | - | 18 |
| 3 | 24 | 19 | 3 | 2 | 19 | 20 |
We clarify the laws of distribution.
Waiting time for loading by vehicles of the I detachment.

Mathematical expectation.
\[ M(\times) = 7 \times 0.04 + 18 \times 0.08 + 25 \times 0.27 + 36 \times 0.11 + 44 \times 0.11 + 58 \times 0.04 + 76 \times 0.08 = 0.28 + 1.44 + 6.75 + 3.96 + 4.84 + 2.32 + 6.08 = 26 \text{ min.} \]

Variance.
\[ D(\times) = (0-26)^2 \times 0.27 + (7-26)^2 \times 0.04 + (18-26)^2 \times 0.08 + (25-26)^2 \times 0.27 + (36-26)^2 \times 0.11 + (44-26)^2 \times 0.11 + (58-26)^2 \times 0.04 + (76-26)^2 \times 0.08 = 182.5 + 14.44 + 5.12 + 0.27 + 11 + 35.64 + 40.96 + 200 = 489.93 \text{ min}^2 \]

Mean square deviation.
\[ \sigma = \sqrt{D(\times)} = \sqrt{489.93} = 22.1 \text{ min.} \]
Waiting time for loading by vehicles of the II detachment.

\[ M(X) = 2 \times 0.17 + 4.5 \times 0.19 + 7.75 \times 0.14 + 12 \times 0.03 + 14 \times 0.16 + 20 \times 0.06 + 25.5 \times 0.06 + 30 \times 0.03 = 0.34 + 0.85 + 1.08 + 0.36 + 2.24 + 1.2 + 1.53 + 0.9 = 8.5 \text{ min.} \]

\[ D(X) = (0 - 8.5)^2 \times 0.16 + (2 - 8.5)^2 \times 0.17 + (4.5 - 8.5)^2 \times 0.19 + (7.75 - 8.5)^2 \times 0.14 + (12 - 8.5)^2 \times 0.03 + (14 - 8.5)^2 \times 0.16 + (20 - 8.5)^2 \times 0.06 + (25.5 - 8.5)^2 \times 0.06 + (30 - 8.5)^2 \times 0.03 \]

\[ = 11.56 + 7.18 + 3.04 + 0.08 + 0.37 + 4.84 + 7.93 + 17.34 + 13.87 = 66.21 \text{ min}^2 \]

\[ \sigma = \sqrt{D(X)} = \sqrt{66.21} = 8.14 \text{ min.} \]

For further calculations, the calculated numerical characteristics of random variables are presented in Table 5.

Table 5. Numerical characteristics of random variables characterizing the operation of harvesting and transport complexes.

| I detachment | TTM brand                     | Indicators               | \( M(X) \) | \( \sigma \) |
|--------------|-------------------------------|--------------------------|------------|------------|
| II detachment| Jaguar 830                    | Vehicle loading time, min.| 9          | 2.37       |
|              |                               | Vehicle waiting time, min.| 2.28      | 4.5        |
|              | Belarus 82.1 + 2PTS-6         | Loading waiting time, min.| 8.5        | 8.14       |

According to the numerical characteristics of random variables calculated on the basis of statistical data, it is possible to determine and monitor the current yield of the harvested crop, which allows to quickly manage the work of the HTC, i.e. optimize its work.

To calculate the yield of the green mass of corn, we use the following formulas:

\[ I_p = \frac{QK \rho ZM \lambda_k}{B \beta U} \]  

(1)
where \( l_P \) is the length of the loading path of the vehicle bed, m;
\( Q_K \) – bed capacity, \( m^3 \);
\( \rho_{ZM} \) is the bulk mass of the green mass of corn, \( t/m^3 \);
\( \lambda_K \) is the filling coefficient of the bed;
\( B \) - width of the header, m;
\( \beta \) – coefficient of header utilization;
\( U \) – yield, t/ha.

The length of the working path of filling the vehicle bed is also calculated using the following formula:

\[
l_P = V t_{ZK} \tag{2}
\]

where \( V \) is the actual working speed of the forage harvester when harvesting corn for silage, km/h;
\( t_{ZK} \) is the time of filling the vehicle bed (mathematical expectation of the time of filling the vehicle bed), h.

Equating the right parts of expressions 1 and 2, we find the yield of an agricultural crop:

\[
U = \frac{Q_K \rho_{ZM} \lambda_K}{V t_{ZK} B \beta} \tag{3}
\]

The yield on the field of the I detachment, when working with the Jaguar 850 forage harvester with the ORBIS 600 SD header, is calculated using the expression 3.

\[
U = \frac{Q_K \rho_{ZM} \lambda_K}{V t_{ZK} B \beta} = \frac{30.77 \times 0.311 \times 1.1}{10 \times 0.37 \times 0.96} = 4.9 \text{ t/ha}
\]

The calculated yield, when working with the Jaguar 850 forage harvester with the ORBIS 450 header, was 5.2 t/ha, the yield on the field of the II detachment, when working with the Jaguar 830 forage harvester, was 5.8 t/ha.

We will simulate the average yield when working with forage harvesters of the I detachment, with the following values of the vehicle loading time: 6,8,10,12,14,16,18,20,22,24,26,28,30. To calculate the simulated yield, we will take the average calculated yield from two harvesters - 5.05 t/ha.

![Figure 7. The ratio of productivity and vehicle loading time.](image-url)
The optimal operation of the harvesting and transport complex is influenced by the yield, the number of forage harvesters and vehicles. Under the actual yield, with a certain number of forage harvesters, using probability theory, mathematical calculations, practical experience, it is possible to select the number of vehicles to ensure optimal operation of the HTC. Using formulas 1-3 and the graph in Figure 7, the work of the harvesting and transport complex can be quickly managed, corrective actions can be made both in terms of the number of forage harvesters and the number of vehicles.

To determine the number of vehicles required to ensure optimal operation of the HTC, we use the following formula [5,6]:

\[
\eta_{TP}^{KUK} = \frac{C_1 T_p}{q_1 t_{ZK}}
\]

where \(\eta_{TP}^{KUK}\) is the number of vehicles required to service one forage harvester, units; 
\(C_1\) – the weight of the green mass in the vehicle bed, t; 
\(T_p\) – duration of the transport cycle, h; 
\(q_1\) – vehicle load capacity, t.

To calculate the number of vehicles, we will take the value "\(t_{ZK}\)" equal to the average time of filling the vehicle body when the Jaguar 850 is operating with an ORBIS 600 SD header and an ORBIS 450 header.

\[
\eta_{TP}^{KUK} = \frac{9.56 \times 1.04}{9.56 \times 0.42} = 2.48 \text{ units}
\]

The average load capacity of the KAMAZ-55102 vehicle with a trailer was 9.56 tons. The volume weight of the green mass of corn for silage, on the day of harvesting, was 0.311 t/m³.

To ensure the operation of the HTC with two forage harvesters, 4.96 units are needed, i.e. 5 transport units. In fact, the green mass was transported by 8 units: KAMAZ-55102 with a trailer - 5 units, tractors ATM - 5280, T-150K with trailers 3PTS-12 - 2 units, tractor Belarus 1221 with a trailer 1PTS-9. When calculating the number of vehicles, the following assumptions were made: a KAMAZ-55102 car with a NEFAZ – 8560 trailer was accepted as a conditional transport unit; ATM – 5280, T-150K tractors with 3PTS-12 trailers – 1.09 units, a Belarus 1221 tractor with a 1PTS-9 trailer - 0.83 units. In total 8.01 units.

To deduce the dependence of the number of vehicles on the yield (vehicle loading time), we use the data from the graph in Figure 7 and Formula 4. The calculation data is presented in Figure 8.

Figure 8. The dependence of the number of vehicles on the yield.
Analysis of the results of the harvesting and transport complex. As a result of the analysis and processing of statistical data, theoretical calculations revealed that for optimal operation of the HTC, consisting of two forage harvesters, five transport units are needed instead of eight. With the existing number of transport units, the idle time for loading was 750 minutes or 15.6% of the working time fund of the transport detachment, idle time of forage harvesters while waiting for transport was 112 minutes or 9.3% of the combine harvesters' working time fund.

4. Conclusion
To increase the efficiency of the HTC, to optimize the work, it was proposed to reduce the number of transport units to six. As a result, the waiting time for loading by vehicles of the I detachment decreased to 570 minutes, decreased by 24% and amounted to 11.9% of the working time fund. Idle time of forage harvesters while waiting for transport was 151 minutes or 12.6% of the combine harvesters' working time fund. The calculation data are shown in Figures 9, 10.

**Figure 9.** Waiting time for loading by vehicles of the I detachment with six vehicles.

**Figure 10.** Waiting time for vehicle by fodder harvestersl detachment with six vehicles.
Calculations on the number of vehicles are made based on statistical data taken during the operation of the HTC at a distance of 10 km from the silo trench. For other transportation distances, correction factors must be applied.

**Table 6.** Correction factors in determining the number of vehicles in the maintenance of the HTC at different transport distances from the field to the silo trench.

| Distance | Up to 5 | 10 | 15 | 20 | 25 | 30 |
|----------|---------|----|----|----|----|----|
| Correction factor | 0.77 | 1.0 | 1.3 | 1.59 | 1.85 | 2.0 |

The table is calculated by the author based on data from the agricultural organization on the location of fields in the fodder crop rotation according to formula 4.

Optimal deployment and management of the work of the HTC affects the efficiency of both forage harvesters and transport on carting.

Research and analysis have shown the following: the cost of transportation, at a constant distance from the field to the silo trench, is affected by vehicle loading time. In our study, the loading time of one vehicle ranged from 11 minutes to 41 minutes. Taking the cost of transportation with a loading time equal to the mathematical expectation of this value – 22 min (0.37 h), per unit, we calculated correction factors for the cost of transportation, with different vehicle loading time. The calculation data are presented in Table 7.

**Table 7.** Correction factors for increasing the cost of transportation depending on the vehicle loading time.

| Loading time, hour | 0.2 | 0.25 | 0.3 | 0.37 | 0.4 | 0.5 | 0.6 | 0.7 |
|--------------------|-----|------|----|------|----|----|----|----|
| Correction factor   | 0.88 | 0.92 | 0.95 | 1.0 | 1.02 | 1.09 | 1.17 | 1.24 |

The table is calculated by the author considering the time of the transport cycle, vehicle loading time (Tables 4, 5).

The efficiency of using forage harvesters is determined by the minimum idle time of the harvesters while waiting for vehicles, at the same time, the number of vehicles, ensuring the smooth operation of forage harvesters, should have minimal idle time.

The domestic [7-9] and foreign authors [10-12] should be noted who deal with the problems of optimizing the work of harvesting and transport complexes when harvesting various crops, i.e., the operational management of the work of the HTC.

**References**

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