A method to improve forwarders’ energy performance and environmental compatibility

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Abstract. The article presents the results of theoretical justifications of a method improving energy performance and environmental compatibility of the load-haul-dump vehicles (forwarders) used during timber cut-to-length operations.

1. Vehicles for timber cut-to-length operation
The basis of the modern mechanized cut-to-length technology are feller-delimber-bunchers (harvesters) and load-haul-dump vehicles (forwarders). The harvesters and forwarders are manufactured both wheel-based and track-based.

There is a big number of manufactures of this type equipment on the market, the harvesters and forwarders are divided into three classes: light, middle and heavy.

The most popular vehicle system for shortwood-at-the stump operation in case clear-cut harvesting is the one comprising an 18-20-ton heavy harvester, an 8-10 m long manipulator boom equipped with a harvester end able to cut trees up to 70 cm in dia. The employed forwarders which come as a set feature a weight of around 20 tons and working load of 17-18 tons.

The performance of such vehicle systems depending on the operation conditions may be up to 350 m³ per day (20 – 25 m³ per hour). Today there is a tendency to increase power and weight characteristics of the vehicles.

During timber logging, a transportation (skidding) operation is the most complex and heavy one in terms of energy performance, production capacity and environmental compatibility. In this regard we have focused on a forwarder (skidder) since the harvester’s energy performance (if we consider a power plant and a need in energy) is mainly dependent on operation of the processing equipment. The harvester does not require slow speed of movement over cutting area, high production capacity during transportation operations. It needs high production capacity during processing operations including felling, knotting, crosscutting: a vehicle remains stationary during those processing operations. It is the opposite with the forwarder: its energy performance depends on speed of loading-hauling (skidding) operations.

The leading scholars note that the design concept of vehicles for cut-to-length technology of timber harvesting is different for a harvester and a forwarder [1-7].

They believe that in case of cut-to-length timber harvesting a forwarder is the vehicle which expends on more energy for movement.
We offer a method to improve energy performance and environmental compatibility of the forwarders as follows.

2. A method to determine output of the forwarder power plant

Wood moisture content and timber species affect the amount of timber taken for transportation (skidding) since the weight impacts the utilization of the forwarder’s lifting capacity. Round wood is calculated as a solid volume of timber by determining the volume of each assortment or stacked volume. To carry out the calculations related to determination of output of the forwarder power plant during loading operations, it is necessary to determine an average mass of 1 m³ of timber each working shift, which can be measured as a quotient obtained when a quantity of loaded tons is divided by a number of cubic meters of the loaded timber.

For example: weight of 1 m³ of timber at moisture of 12% stands for birch at 630-650 kg; for European aspen at 470-490 kg; for oak at 680-720 kg; for fir at 440-460 kg; for pine at 370-600 kg; for larch at 650-800 kg. For easy calculation we use tons instead of m³.

Let us determine the harvester performance (\( P_{SMH} \)).

\[
P_{SMH} = \frac{M_{GR}}{T_X} \tag{1}
\]

where: \( M_{GR} \) is mass of assortment cut by the harvester; \( T_X \) is time of approach, felling, knotting and crosscutting during harvesting of assortment of mass \( M_{GR} \); Let us determine performance of the forwarder or its load flow (\( P_{SMF} \)).

\[
P_{SMF} = \frac{M_{GRF}}{T_F} \tag{2}
\]

where: \( M_{GRF} \) is mass of assortment hauled on the log deck at the storage place; \( T_F \) is time for loading and hauling of assortment of mass \( M_{GRF} \); Condition \( P_H = P_F \).

Given that \( S_H \) is a path passed by the harvester during cutting assortment of mass \( M_{GR} \) for a time of \( P_{GR} \). Let’s determine the forwarder performance (\( P_{GR} \)) during loading or unloading of assortment of mass \( M_{GRF} \) for a time of

\[
T_{pogri/razgr}.P_{GR} = \frac{M_{GRF}}{T_{pogri/razgr}} \tag{3}
\]

Let us determine a coefficient of utilization of the forwarder mass (\( k_{mf} \))

\[
k_{mf} = \frac{M_{grf}}{M_f} \tag{4}
\]

where: \( M_f \) is the forwarder mass.

Assumptions:
1) The forwarder follows the harvester’s path.
2) The forwarder’s resistance-to-movement coefficient does not change depending on the number of passages and forwarder mass.
3) Transmission efficiency is equal to 1; no slipping.

The mass \( M_{GR} \) of assortment cut by the harvester is equal to the mass \( M_{GRF} \) of assortment hauled by the forwarder to the log deck.

Solution:
Time \( T_F \) of forwarder one trip includes: time of empty forwarder movement from a loading site to an assortment load collection site, time to pick up a load, time of loaded forwarder movement to a loading site, time to unload assortment from the forwarder to a stack, min.

\[
t_n = \frac{M_{gr}}{P_{gr}} \tag{5}
\]

\[
t_{gr} = \frac{S_i}{V_{gr}} \tag{6}
\]

\( t_{gr} \) is time of loaded forwarder movement over path \( S_i \) at speed \( V_{gr} \).

The speed of movement of the forwarder loaded with assortment to the loading site can be determined as follows
\[ V_{gri} = \frac{N_{dvf}}{(M_f + M_{grf})} \cdot f \cdot g \]
\[ T_{dvig} = \sum_{i=1}^{n} t_{gri} \]

where: \( f \) is a summing coefficient of resistance to movement; \( n \) is number of passages from the harvester cutting site to the log deck; \( N_{dvf} \) is forwarder engine power;
\[ t_{b/gri} = \frac{s_i}{V_{b/gri}} \]

\( t_{b/gri} \) is time of empty movement over path \( S_i \) at speed \( V_{b/gri} \).
\[ V_{b/gri} = \frac{N_{dv}}{M_f} \cdot f \cdot g \]
\[ T_{dvig b gru} = \sum_{i=1}^{n} t_{b/gri} \]

where: \( n \) is number of skiddings (passages) from the harvester cutting site to the log deck.
\[ T_f = 2 \frac{M_{gr}}{V_{gr}} + \sum_{i=1}^{n} \frac{S_i M_f g}{N_{dv}} + \sum_{i=1}^{n} \frac{S_i M_f f g}{N_{dv}} \]
\[ T_f = \frac{2M_{gr}}{V_{gr}} + \frac{2M_f f g}{N_{dv}} \sum_{i=1}^{n} + \frac{f g}{N_{dv}} \sum_{i=1}^{n} + \frac{f g}{N_{dv}} \sum_{i=1}^{n} S_i M_{grf} \]

The specificity of processing operation of the mechanized cut-to-length technology is that the forwarder always follows the harvester. The forwarder reaches the harvester, loads the assortment and moves back to the log deck or hauling road and this repeats several time per shift. If we know the harvester’s performance, performance of the loading-unloading operations of the forwarder, then we can determine the general level of the designed structure of the forwarder (\( k_{mh} \)). Then we determine or select the harvester’s performance. It can be different but for the sake of calculation we shall specify high performance figure. High performance figures shall also be specified for loading-unloading equipment installed on the forwarder. \( S_X \) is a path passed by the harvester but not the vehicle’s movement: it is related to the frequency of trees location on the cutting area.
\[ N_{dv} = \frac{f g s_h (\frac{1}{s_{mf}} + \frac{1}{s_{gf}})}{(\frac{1}{s_{mf}} + \frac{1}{s_{gf}})} \]

This equation is convenient for use, if we specify the performance, then we can obtain the engine power, if we divide the engine power by \( f \) and \( g \) and specify movement speed, average speed (for example, 10 km/h), then we obtain average mass, since a speed in one direction and the other differs, the power curve is hyperbolic. We obtain a mass, then using a coefficient of forwarder mass utilization we find the amount of assortment to be carried by the forwarder and then go to transportation operation.

This formula can be developed as follows:
- first development, the forwarder always follows the harvester and repeats the same path, another model of the forwarder movement can be selected depending on how it moves between the cutting areas and collects assortment loads;
- second development, it is necessary to create different resistance to movement of the loaded and empty forwarder. It is clear that the coefficient of resistance to movement does not depend on mass, but soil pressure varies depending on whether the forwarder is empty of loaded and thus depends on the damaged soil;
- third development, a coefficient of resistance to movement depends on the number of passages. But the model operating principle is more understandable in this form with due consideration of the taken assumptions. It is necessary to check the obtained conclusions through modelling in the applied program packages. Further development of the proposed formula is as follows: for example, resistance to movement decreases, the consumed engine power drops, we alternatively increase and reduce it and then determine the number of forwarders required to have time to complete handling operations after the harvester depending on the cutting area type, wood density and volume, as well as on the path passed.
the harvester and its performance. The proposed model skips the economic issues as other researchers in this field do [8-12].

The principle of this model consists in that the performance of the felling-knotting-crosscutting operations is equal to performance of the handling operations, so neither harvester nor forwarder is idle. We obtained a dependency which helped us to find out that very fast riding over cutting area is possible but it leads to transportation of small load (assortment volume) since the power output is pre-determined: if small load needs to be carried then it requires fast riding, if slow riding is required then heavy loads shall be carried.

The balance rational design of the forwarder’s construction for the specific conditions of timber harvesting will be specified with due consideration for the harvester’s performance, forwarder’s resistance to movement \( f \) and number of its passages. This model allows for the following main conclusion – the harvester’s performance shall be equal to the forwarder’s load flow (everything cut by the harvester shall be picked up by the forwarder). If the harvester’s performance rises, the path passed increases, then the forwarder will not be able to keep pace with the harvester, so the forwarder requires a running gear with high off-road performance, travel speed and lifting capacity, and more productive processing equipment needs to be employed. Should the proposed measures fail to improve the forwarder’s situation, then it will be necessary to use two forwarders for timber cutting. However this is a different model. As an example, \( f \) varies depending on whether the forwarder which moves over a forest swath is loaded or empty, as well as on a number of its passages, etc.

The scientific novelty is as follows. The forwarder engine power has been obtained taking into account the principles of equality of the forwarder load flow, harvester’s performance, that helps to specify the design of the developed vehicle basing on the resistance to movement and the path to be passed by the harvester depending on the stand density. 

\( T_H \) is time of the harvester felling-knotting-crosscutting operations and movement to the next tree, use is made of the function which links the stand density and performance of the processing equipment of the manipulator and harvester end.

In order to use this formula

\[
N_{dv} = \frac{f \cdot g \cdot S_H \left( \frac{1}{m_f} \right)^{1/2}}{\left( \frac{1}{P_H} + \frac{2}{P_{gr}} \right)}
\]

(15)

Coefficients \( P_H \) and \( P_{gr} \) if unknown shall be experimentally found through work measurements of the harvester and forwarder operation. \( P_H \) and \( P_{gr} \) are taken as kg per sec for easy calculation.

The proposed calculation procedure allows for defining a propulsion unit type and design of the forwarder running gear at the forwarder construction designing stage.

The forwarder’s path changes as the harvester constantly moves further.

Figure 1. Assortment taken away in one passage
Figure 2. Assortment taken away in two passages

Figure 1 shows the first case when a number of passages is equal to one, the harvester has cut wood, the forwarder has quickly arrived and picked up all ready assortment and taken it on the log deck.

Definition
\[ \sum_{i=1}^{n} S_i \]  

\( a) \) Option \( n = 1 \)
\[ \sum_{i=1}^{n} S_i = S_H \]  
where: \( S_H \) – harvester path; \( S_f \) – forwarder path.

Figure 2 shows the second case when the harvester continues moving over the forest swath, the forwarder covers a path \( n = 2 \) to the midway, then it leaves for unloading and arrives to the loading site.

\( b) \) Option \( n = 2 \)
\[ \sum_{i=1}^{n} S_i = S_H^2 + S_H \cdot \frac{2}{2} \]  

The same is for path \( n = 3 \) and so on for each and every trip till the end of the shift.

\( c) \) Option \( n = 3 \)
\[ \sum_{i=1}^{n} S_i = S_H^3 + \frac{2}{3} S_H + S_H \cdot \frac{3}{3} \]  
\[ \sum_{i=1}^{n} S_i = \frac{S_H \cdot \sum_{i=1}^{n} \frac{1}{2}}{n} = \frac{n \cdot (n+1)}{2} \]  
\[ \sum_{i=1}^{n} S_i = \frac{S_H \cdot (n+1)}{2} \]  

Next presented is a very interesting case when \( n = 2 \), i.e. the forwarder has once covered half-distance and once till the end. \( S_i \) is the forwarder’s path in one direction. The more the harvester operates \( S_H \), the more precise is calculation, since \( S_H \) is a path passed by the harvester while cutting assortment of mass \( M_{gr} \) for the time \( t_H \) per shift. The longer is \( S_H \), the easier to neutralize the power oscillations. \( S_H \) depends on stand density at the developed cutting area.

Prior to calculations it is necessary to obtain data on the stand characteristics, species composition, diameter, etc.

Definition:
\[ M_{gr} = \sum_{i=1}^{n} M_{grf} = P_f M_{grf} \]  
\[ T_f = \frac{2M_{gr}}{P_{gr}} + \frac{f \cdot g}{N_{dv}} \left( 2M_f + M_{grf} \right) \frac{S_H (n+1)}{2} = \frac{M_{gr}}{P_H} \]  
\[ \frac{1}{P_H} = \frac{2}{P_{gr}} + \frac{f \cdot g}{N_{dv}} \frac{S_H (n+1)}{2} \left( \frac{2M_f + M_{grf}}{M_{grf}} \right) \]
\[
\frac{1}{n} \rightarrow \left(\frac{M_{grf}}{M_{gr}}\right)
\]
(25)

\[
\frac{1}{P_H} = \frac{2}{P_{gr}} + \frac{f g S_H (n+1)}{N_{dv} 2} \left(\frac{2}{n \cdot k_{mf}} + \frac{1}{n}\right)
\]
(26)

assuming that \(n > 20\)

\[
\frac{n + 1}{n} \approx n
\]
(27)

\[
\frac{n+1}{n} \approx 1
\]
(28)

\[
\frac{1}{P_H} = \frac{2}{P_{gr}} + \frac{f g S_H \left(\frac{1}{k_{mf}} + \frac{1}{2}\right)}{N_{dv}}
\]
(29)

\[
N_{dv} = \frac{f g S_H \left(\frac{1}{k_{mf}} + \frac{1}{2}\right)}{\left(\frac{1}{P_H} - \frac{2}{P_{gr}}\right)}
\]
(30)

This method is applicable to the harvesting vehicles with wheeled, tracked and combined running gear. The engine power calculation formula (30) includes \(f\) as a total coefficient of resistance to movement which impacts selection of the running gear type. For example, wheel running gear is employed in case of minor resistance, if resistance rises then wheeled-tracked gear is used, high resistance requires tracked running gear. The total coefficient of resistance to movement \(f\) depends on soil category and its bearing capacity. The method will further focus on slipping of the harvesting vehicle running gear.

3. Coefficient of resistance to movement

Our model of forwarder selection shall be added with required power, specific characteristics of the cutting area, its length and width, stand volume and density, estimated harvester capacity per shift, coefficient of utilization of the forwarder mass.

Main stipulations and assumptions

1. Forwarder capacity (per shift) is a lifting capacity is equal to harvester capacity (per shift);
2. Resistance-to-movement along the forwarder travel changes after it takes load (assortment) only;
3. Coefficient \(f\) is an initial value of resistance-to-movement.

Coefficient \(\Delta f\) stands for variation of resistance-to-movement per each trip.

\[
T_f = 2 \frac{M_{gr}}{P_{gr}} + \sum_{i=1}^{n} \frac{S_i (M_f + M_{grf}) t_i \alpha}{N_{dv}} + \sum_{i=1}^{n} \frac{S_i M_f t_i \alpha}{N_{dv}}
\]
(31)

where: \(\frac{2 M_{gr}}{P_{gr}}\) is time of forwarder loading and unloading; \(\sum_{i=1}^{n} \frac{S_i (M_f + M_{grf}) t_i \alpha}{N_{dv}}\) is time of loaded forwarder movement; \(\sum_{i=1}^{n} \frac{S_i M_f t_i \alpha}{N_{dv}}\) is time of empty forwarder movement; \(n\) is number of passages (during movement of both empty and loaded vehicle).

\[
T_f = 2 \frac{M_{gr}}{P_{gr}} + \frac{\alpha}{N_{dv}} \left(\sum_{i=1}^{n} S_i t_i\right) (2M_f + M_{grf})
\]
(32)

Let us find

\[
\sum_{i=1}^{n} S_i t_i
\]
Figure 3.

Third passage

\[(S_3 - S_2)f_0 + (S_2 - S_1)(f_0 + \Delta f) + S_1(f_0 + 2\Delta f) = S_3 \cdot f_0 + S_2 \Delta f + S_1 \Delta f = S_3 f_0 + \sum_{i=1}^{n} S_i \Delta f \tag{33}\]

\[n\text{-passage}\]

\[S_n f_0 + \sum_{i=1}^{n-1} S_i \Delta f \tag{34}\]

\[\sum_{i=1}^{n} S_i f_i = \sum_{i=1}^{n} (S_i f_0 + \sum_{j=1}^{i-1} S_j \Delta f) = f_0 \sum_{i=1}^{n} S_i + \Delta f \cdot \sum_{i=1}^{n} S_j(i) \tag{35}\]

The forwarder has made \(n\)-number of passages, for example 20, resistance changes, that is quite a total resistance which is finally found through approximation.

\[\sum_{i=1}^{n} S_i t_i = \frac{f_0 S_H}{n} \sum_{i=1}^{n} i + \frac{\Delta f S_H}{n} \sum_{i=1}^{n} \sum_{j=1}^{i-1} j \tag{36}\]

\[\sum_{i=1}^{n} \sum_{j=1}^{i} \frac{(i-1)i}{2} = \frac{n(n+1)(2n+1)}{6} \tag{37}\]

\[\sum_{i=1}^{n} \sum_{j=1}^{i} \frac{i^2}{2} = \frac{n(n+1)(2n+1)}{12} \tag{38}\]

\[\sum_{i=1}^{n} \sum_{j=1}^{i} \frac{i^3}{3} = \frac{n(n+1)(n+2)(2n+1)}{24} \tag{39}\]

\[T_f = 2 \frac{M_{gr}}{P_{gr}} + \frac{g(2M_{gr} + M_{gf}) S_H (f_0 + \Delta f(n-1))(n+1)}{N_{dv} \cdot 2} \tag{40}\]

\[\frac{1}{P_H} = \frac{2}{P_{gr}} + \frac{g S_H (f_0 + \Delta f(n-1))}{N_{dv} \cdot \frac{1}{2} \cdot \frac{3}{2}} \tag{41}\]
With due regards for:

\[ M_{gr} = n \cdot M_{grf} \] (44)

Then multiply \( \Delta f \) by \( n \) minus one plus \( f_0 \) – this is quite a final total resistance. In other words, there is certain resistance prior to movement in the field, after a vehicle has made \( n \)-number of passages, for example 20, resistance changes. That is quite a total resistance which is finally found through approximation.

\[
N_{dv} = \frac{gS_H}{1 - \frac{1}{k_{mf} \cdot P_{gr}}} \left( 1 + 1 - \frac{n+1}{2} \right) \frac{n+1}{n} \left( f_0 + \frac{\Delta f(n-1)}{3} \right)
\] (45)

Let's set the expression to \( A \)

\[
N_{dv} = \frac{gS_H}{1 - \frac{1}{k_{mf} \cdot P_{gr}}} \left( 1 + 1 - \frac{n+1}{2} \right) \frac{n+1}{n} \left( f_0 + \frac{\Delta f(n-1)}{3} \right) = A \left( f_0 + \frac{\Delta f(n-1)}{3} \right)
\] (46)

\[
\frac{\partial N_{dv}}{\partial n} = A \frac{\Delta f(n-1)}{3n^2} = A \frac{\Delta f}{3n^2}
\] (47)

\[
\frac{\partial n^*}{\partial N_{dv}} = \frac{1}{A} \left( f_0 - \frac{\Delta f}{3} \right)
\] (48)

where: \( n^* \) - number of passages per shift corresponds to the minimum estimated engine power \( \text{min}N_{dv} \)

\[
\frac{\partial^2 N_{dv}}{\partial n^2} = A \left( f_0 - \frac{\Delta f}{3} \right) \frac{2}{n^3}
\] (49)

For example, if we take the forwarder movement speed equal to 10 km/h, skidding distance of 300 m.

Calculation example at \( f_0=0.1; \Delta f=0.008 \) number of passages per shift is equal to six.

\[
n^* = \frac{3f_0 - 0.008}{\frac{3f_0 - 0.008}{6} - 1} = 6.123724 \approx 6
\]

4. Running gear slipping correction

The following relationship has been obtained to find required power for the forwarder running gear drive with due consideration for a change in resistance to movement

\[
\frac{1}{P_{SM}} = \frac{2}{P_{gr}} + \frac{gS_H(f_0 - \frac{\Delta f(n-1)}{3})}{n} \frac{1}{N_{dv}} \frac{n+1}{n} \frac{3}{2}
\] (50)

where: \( n \) - number of the loaded forwarder passages; \( \Delta f \) is increase in resistance to movement per one pass of the loaded forwarder; \( N_{dv} \) is dependence on change in the forwarder resistance to movement.

The relationship is obtained with due consideration for the running gear slipping correction

1) Suppose \( n \gg 1 \rightarrow \frac{n+1}{n} \approx 1; \)

where: \( n \) – number of passages

2) \( f_0 + \Delta f(n-1) = f_{max} \)

where: \( f_0 \) is initial resistance to movement; \( f_{max} \) is forwarder resistance to movement after \( n \)-passages

For example:

Dry earth road \( \rightarrow \) bumpy earth road; Suppose \( G_0 \) is running gear slipping at \( f_0 \);

\[
G = \frac{\omega Z_0 - V}{\omega Z_0}
\]

where: \( Z_0 \) is radius of the driving wheel; \( G_{max} \) is running ear slipping at \( f_{max} \).

\[
N_{dv} = \frac{N_{dv}}{1 - G}
\]

\[
N_{dv} = fmgV + R(x(\omega Z_0 - V) = fmg\omega z_0 = \frac{fmgV}{1 - G}
\]
Specific energy consumption per unit of the passed path during movement for loading, \( f_w = \frac{N_{dvig}}{mgv} \),

coefficient of free thrust \( K_T = \frac{p_T}{mg} \)

\[
f_w = \frac{1}{3} (3f_0 + \Delta f(n - 1)), \quad \frac{1}{P_{SMH}} = \frac{2}{P_{gr}} + \frac{gs_H(2f_0 + f_{max})(\frac{1}{kmf} + \frac{1}{2})}{3N_{dvig}}, \quad \frac{1}{P_{SMH}} = \frac{2}{P_{gr}} + \left(\frac{1}{kmf} + \frac{1}{2}\right) \frac{gs_X(2f_0 + f_{max})(1 - g_{0})}{3N_{dvig}}
\]

Resistance to movement varies depending on the number of passages, as the skidding track (road/path) gets broken, the movement becomes more difficult, then we abandon the wheeled running gear in favor of the tracked one, and if the skidding track is not broken we continue using the wheeled gear.

The proposed method is for every occasion. For example, if we have ten harvesters operating, how many forwarders do we need and what shall be their power? Will it be dry or wet? Will the snow be deep? What shall we drive, how much shall we carry? What type of vehicle is required? Etc. When we consider the running gear, we need to know its specific capacity. It can be assumed that transmission is continuously variable. We do not consider speeds but shifts and passed path.

5. Conclusion
Based on the presented calculations, the engine power does not depend on the amount of assortment the forwarder carries (skids) but on the technical level of the harvester’s performance, stand (forest) density
and loading-unloading operations. This conclusion needs to be proved, to do so it is necessary to simulate the proposed equation.

The proposed calculation method allows for determining a type of running gear and design of the undercarriage of the forwarder at the forwarder designing stage.

The harvester’s performance shall be equal to the forwarder’s load flow (everything cut by the harvester shall be picked up by the forwarder).

It is necessary to draw a table of a coefficient of utilization of the forwarder mass which is based on the amount of assortment carried and the forwarder’s own mass at the moment.

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