Analysis of power efficiency and agility of a combination vehicle with active semi-trailer by mathematical simulation

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Abstract. This article gives an estimate of power consumption at curves and the swept path width for a combination vehicle with steered and non-steered wheels of semi-trailer. Several options of power distribution between the combination vehicle sections are discussed.

1. Introduction
The use of combination vehicles is highly promising in industrial and rural areas with underdeveloped road network, i.e. impassability of roads, which is especially relevant for our country [1]. Nowadays, off-road combination vehicles come into use in timber industry and also in construction and servicing of oil and gas pipelines. However, their application is oftentimes limited due to insufficient traction capacity [2]–[5]. Developing combination vehicles with sufficient traction dynamics is thus a very topical applied research task, and one of effective solutions to it is implementation of trailers with driven wheels [6]–[7].

2. Theory
The subject of research is a combination vehicle with 120,000 kg GVW consisting of a four-axle tractor with electromechanical transmission (EMT) and a three-axle semi-trailer.

In the base case (combination vehicle with a semi-trailer having non-driven wheels), each wheel is driven by a 60 kW traction electric motor (TEM). So, the total power of all TEMs of the tractor is 480 kW. This is the maximum power transmitted from the engine to TEMs. The power of TEMs of a combination vehicle with all driven wheels has been selected so as to have equal power-to-weight ratio in all cases.

Four power distribution cases are discussed: the first one implies concentration of power in the tractor wheels only (base case), the second one – 25% of the total power in semi-trailer wheels, the third one – 50%, and the last one – 75%. Figure 1 shows power distribution among combination vehicle wheels.
Figure 1. Power distribution (%) among combination vehicle wheels:

\( a - 100/0; b - 75/25; c - 50/50; d - 25/75. \)

Steering pole of the tractor is located on the third axis. Minimum width of the swept path is ensured if the semi-trailer rear axle center travels along the hitch point path [8]. Figure 2 shows a calculation diagram for semi-trailer wheel steering angles.

Figure 2. Calculation diagram for turning motion of a two-section trailer truck.
If we accept that a combination vehicle is moving with no drift, then the jackknifing angle can be expressed through the driving wheel steering angle (for “driving”, we take a conventional wheel which is in the center of the tractor front axle):

\[ \theta_s = \arcsin \left( \frac{l_{s3} \cdot \tan \theta_s}{2 \cdot l_{13}} \right) \]  

(1)

where \( \theta_s \) – combination vehicle jackknifing angle, rad; \( \theta_s \) – driving wheel steering angle, rad; \( l_{s3} \) – distance between the kingpin and the 3rd axle of the semi-trailer, m; \( l_{13} \) – distance between the 1st and 3rd axles of the tractor, m.

Then, semi-trailer wheel steering angles are:

\[
\begin{aligned}
R_{\text{kin}2} &= \frac{l_{sp}}{\tan \theta_{w2i}}; \\
\theta_{w2i} &= \arctg \left( \frac{l_{sp} - l_{w}}{R_{\text{kin}2} \pm 0.5 \cdot B_2} \right),
\end{aligned}
\]  

(2)

where \( l_{sp} \) – distance between the kingpin and the semi-trailer turning center, m; \( R_{\text{kin}2} \) – theoretical radius of the semi-trailer turn, m; \( \theta_{w2i} \) – i-wheel steering angle, rad; \( B_2 \) – semi-trailer track width, m.

Actual turning radius and turning center shift for the tractor can be calculated subject to known components of linear speed of center of mass and angular turning rate (see figure 3):

\[
\begin{aligned}
R_{p1} &= \frac{v_{Cx}}{\omega_{z1}}; \\
R_{C1} &= \frac{v_{C}}{\omega_{z1}}; \\
l_{Cp} &= \sqrt{R_{C1}^2 - R_{p1}^2},
\end{aligned}
\]  

(3)

where \( R_{p1} \) – actual turning radius of the tractor, m; \( R_{C1} \) – turning radius of center of mass of the tractor, m; \( v_{Cx} \) – longitudinal component of tractor linear speed, m/s; \( V_C \) – tractor linear speed, m/s; \( \omega_{z1} \) – tractor angular speed, s\(^{-1}\); \( l_{Cp} \) – distance between the center and the center of mass of the tractor, m.

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**Figure 3.** Calculation diagram of a tractor turn.
In this case, radii of tractor wheel trajectory can be calculated using the following formula:

\[
R_{wi} = \sqrt{\left(l_{cp} + x_{wi}\right)^2 + \left(R_{pl} - y_{wi}\right)^2},
\]

where \(x_{wi}, y_{wi}\) are coordinates of \(i\)-wheel with respect to the center of mass of the tractor, m.

The same formula can be used to find center position and actual radius of turn for a semi-trailer. Specific power consumption during a turn can be evaluated with delivered power factor [9]:

\[
f_N = \frac{N_{ap}}{G_{ap} \cdot V_C},
\]

where \(N_{ap}\) – required power, W; \(G_{ap}\) – combination vehicle weight, N.

Calculation algorithm for the required swept path width (\(H_k\)) and estimation algorithm for specific power consumption (\(f_N\)) required for a combination vehicle to perform a turn with a pre-defined radius should be as follows:

1) Select theoretical turning radius value being studied.
2) Define steering angles of steered wheels which correspond to the theoretical turning radius (according to turning center position).
3) Combination vehicle speed should be maintained constant throughout modeling.
4) When stable parameters of the turn are reached, stop modeling process and make record of radii of combination vehicle wheel trajectories, as well as actual turning radii of the sections and the required power value.
5) Calculate required swept path width for travel with a pre-set radius and value of the delivered power factor.
6) Proceed with the next value of the theoretical radius of turn.

3. Research results
The mathematical model is described in [10]. The study included 9 fixed values of turning radius within the range of 12 to 150 m. Four options of power distribution between the sections were considered (as shown in Fig. 2) with regard to a combination vehicle turn with steered and non-steered wheels of a semi-trailer.

Tables 1 and 2 as well as figures 4 and 5 show calculation results (the figures do not show all the results).

**Table 1.** Required swept path width and delivered power factor for a combination vehicle with non-steered wheels of a semi-trailer.

| Turning radius (theoretical), m | Power distribution 100/0 | Power distribution 75/25 | Power distribution 50/50 | Power distribution 25/75 |
|-------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| \(H_k, \text{ m}\) | \(f_N\) | \(H_k, \text{ m}\) | \(f_N\) | \(H_k, \text{ m}\) | \(f_N\) | \(H_k, \text{ m}\) | \(f_N\) |
| 12  | 11.680 | 0.05997 | 12.510 | 0.06202 | – | – | – | – |
| 15  | 8.473 | 0.04975 | 8.578 | 0.05107 | 8.735 | 0.05326 | 9.044 | 0.05752 |
| 20  | 6.672 | 0.0403 | 6.704 | 0.04084 | 6.743 | 0.04159 | 6.792 | 0.04265 |
| 25  | 5.792 | 0.03403 | 5.809 | 0.03432 | 5.829 | 0.03470 | 5.852 | 0.03525 |
| 35  | 4.870 | 0.02735 | 4.878 | 0.02746 | 4.888 | 0.02762 | 4.898 | 0.02783 |
| 50  | 4.210 | 0.02311 | 4.214 | 0.02316 | 4.219 | 0.02322 | 4.224 | 0.02332 |
| 75  | 3.707 | 0.02054 | 3.708 | 0.02054 | 3.711 | 0.02056 | 3.714 | 0.0206 |
| 100 | 3.457 | 0.01954 | 3.460 | 0.01953 | 3.459 | 0.01954 | 3.464 | 0.01957 |
| 150 | 3.203 | 0.01878 | 3.203 | 0.01877 | 3.217 | 0.01877 | 3.216 | 0.01879 |
Table 2. Required swept path width and delivered power factor for a combination vehicle with steered wheels of a semi-trailer.

| Turning radius (theoretical), m | Power distribution 100/0 | Power distribution 75/25 | Power distribution 50/50 | Power distribution 25/75 |
|-------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
|                               | $H_k$, m                 | $f_N$                    | $H_k$, m                 | $f_N$                    |
| 12                            | 4.791                    | 0.04297                  | 4.786                    | 0.04345                  | 4.783                    | 0.04402                  | 4.789                    | 0.04482                  |
| 15                            | 4.421                    | 0.03219                  | 4.422                    | 0.03241                  | 4.425                    | 0.03269                  | 4.430                    | 0.03305                  |
| 20                            | 3.983                    | 0.02417                  | 3.985                    | 0.02427                  | 3.987                    | 0.02438                  | 3.990                    | 0.02451                  |
| 25                            | 3.741                    | 0.02107                  | 3.742                    | 0.02111                  | 3.744                    | 0.02117                  | 3.746                    | 0.02124                  |
| 35                            | 3.440                    | 0.01913                  | 3.441                    | 0.01914                  | 3.442                    | 0.01916                  | 3.444                    | 0.01920                  |
| 50                            | 3.220                    | 0.01846                  | 3.221                    | 0.01846                  | 3.221                    | 0.01846                  | 3.222                    | 0.01848                  |
| 75                            | 3.046                    | 0.01824                  | 3.047                    | 0.01822                  | 3.047                    | 0.01822                  | 3.048                    | 0.01823                  |
| 100                           | 2.960                    | 0.01818                  | 2.961                    | 0.01816                  | 2.961                    | 0.01816                  | 2.961                    | 0.01817                  |
| 150                           | 2.874                    | 0.01815                  | 2.874                    | 0.01813                  | 2.874                    | 0.01812                  | 2.874                    | 0.01813                  |

Figure 4. Variation of required swept path width with respect to turning radius.
As seen from Table 1, higher traction in semi-trailer at small turning radius results in a wider swept path and higher delivered power factor and in some cases (turning with theoretical radius of 12 m for power distribution cases 50/50 and 25/75) makes it impossible to perform a maneuver due to combination vehicle jackknifing (see figure 6).

For a combination vehicle with steered semi-trailer wheels, increase in power rate delivered to the wheels of a hitched section has almost no impact on trajectory of its motion (see figure 7) or on the delivered power factor.
Figure 7. Motion trajectory of a combination vehicle with steered semi-trailer wheels (theoretical turning radius of 12 m) for 2 cases of power distribution between sections.

4. Conclusions
The study has shown that use of steered wheels in a semi-trailer allows for significant reduction (especially at small turning radii) of the required width of the swept path and power consumption during the maneuver.

For a combination vehicle with semi-trailer having all driven wheels, using steered wheels within the studied modes of motion allows avoiding intensive jackknifing.

Further study should aim at development of automatic control of steering and all-wheel drive, finding solution for research and practical task on optimization of the power distribution parameters using various electronic control systems, including those based on analysis of forces acting in the hitching device.

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