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(54) **Title:** LONGITUDINAL TYRE FORCE ESTIMATION

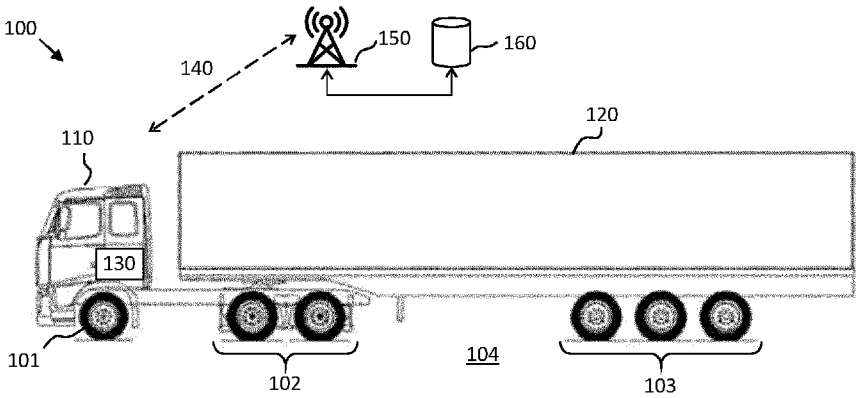


FIG. 1

(57) **Abstract:** A computer system (130, 800) for controlling motion of a heavy-duty vehicle (100), the system comprising at least one tyre belt speed sensor (260) according to any of claims 1-7, at least one axle speed sensor (250), and processing circuitry, where the axle speed sensor (250) is arranged to determine an angular speed (ω_m) of a drive axle associated with a wheel (101, 102, 103, 200) of the heavy-duty vehicle (100) that supports the tyre (215), and to output data indicative of the angular speed (ω_m) of the drive axle on an axle speed sensor output port, where the processing circuitry is arranged to receive the data indicative of the angular speed (ω_m) of the drive axle and the data indicative of the angular speed (ω_m) of the tyre belt (210), and0 where the processing circuitry is arranged to determine a longitudinal tyre force (F_x) associated with the wheel (101, 102, 103, 200) based on the data indicative of the angular speed (ω_m) of the drive axle and based on the data indicative of the angular speed (ω_b) of the tyre belt (210).

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LONGITUDINAL TYRE FORCE ESTIMATION

TECHNICAL FIELD

This disclosure relates generally to control of heavy-duty vehicles such as trucks, busses, and construction equipment. In particular aspects, the disclosure relates to systems and methods for estimating a longitudinal tyre force generated by one or more wheels on a heavy-duty vehicle, and also to systems and methods for detecting tyre explosion. Although the disclosure may be described with respect to a particular vehicle, the disclosure is not restricted to any particular vehicle or vehicle type.

BACKGROUND

Tyre force is the force generated between the road surface and the wheels of a vehicle. This tyre force is what moves the vehicle over the road surface. A positive tyre force resulting from torque applied by a propulsion device, such as a combustion engine or an electric machine, will accelerate the vehicle as long as it overcomes losses from, e.g., air resistance and rolling resistance. Braking by an actuator such as a friction brake or an electric machine generates a negative tyre forces that will decelerate the vehicle.

Measuring the tyre force generated at one or more wheels of a heavy-duty vehicle is challenging. Approaches for determining tyre force based on conversion between wheel slip and tyre force have been proposed previously in, e.g., EP3851346A1. However, alternative methods are desired.

SUMMARY

The present disclosure relates to sensors, methods, and systems for estimating and/or controlling motion by a heavy-duty vehicle, such as determining longitudinal tyre force and detecting tyre explosion. Some of the techniques disclosed herein may be described in terms of a computer system and/or as methods performed by the computer system.

Among other things, the disclosure relates to a tyre belt speed sensor for a heavy-duty vehicle. The sensor comprises a sensor front end configured to sense motion of an outer surface of a tyre, where the outer surface of the tyre is arranged to engage a road surface supporting the heavy-duty vehicle in use. The sensor also comprises a sensor back end configured to determine data indicative of an angular speed of a tyre belt of the tyre based on the motion sensed by the sensor front end, and an output port arranged to output the data indicative of the angular speed of the tyre belt. Several applications can be realized based on the data indicative of the angular speed of the tyre belt. For instance, a tyre explosion can be

detected with low latency and high reliability by monitoring the tyre belt speed and looking for a disturbance in the tyre belt speed data. The tyre belt speed can also be combined with axle speed data in order to determine tyre longitudinal force, and also to get an idea about current road friction conditions. Both the tyre longitudinal force data and the data related to current road friction conditions are helpful when controlling motion by a heavy-duty vehicle.

The sensor front end may, e.g., be realized by a vision-based sensor, a radar transceiver, a roller wheel arrangement, a vibration pick-up member, and/or a Hall effect sensor. In other words, the sensor front end may be realized in many different ways. The sensor front end may comprise one or more sensor devices based on one or more sensor techniques for increased reliability. The cost of the sensor front end varies with the selected sensor technique, which means that the sensor can be produced cost-efficiently if a low-cost technique is selected, or as a more high performing sensor if a more expensive sensor technique is selected.

The sensor back end may, as noted above, be configured to detect a tyre explosion of the tyre based on a detected disturbance in the sensed motion of the outer surface of the tyre. This detection technique offers reliable tyre explosion detection with low latency, which is an advantage. It is advantageous to perform tyre explosion detection directly using tyre belt speed data, which is immediately affected by the explosion, instead of more indirect data such as vehicle motion data or wheel speed data, since it takes some time for the tyre explosion to have an effect there.

The present disclosure also relates to a computer system for controlling the motion of a heavy-duty vehicle. The system comprises at least one tyre belt speed sensor as discussed above, at least one axle speed sensor, and processing circuitry. The axle speed sensor is arranged to determine an angular speed of a drive axle associated with a wheel of the heavy-duty vehicle that supports the tyre, and to output data indicative of the angular speed of the drive axle on an axle speed sensor output port. The processing circuitry is arranged to receive the data indicative of the angular speed of the drive axle and the data indicative of the angular speed of the tyre belt. The processing circuitry is also arranged to determine a longitudinal tyre force associated with the wheel based on the data indicative of the angular speed of the drive axle and based on the data indicative of the angular speed of the tyre belt. This way tyre longitudinal force can be determined in a reliable manner and at relatively low cost, which is an advantage. The tyre longitudinal force information is very useful when controlling motion by the heavy-duty vehicle.

According to some aspects, the processing circuitry is also arranged to obtain data indicative of a wheel slip associated with the tyre, and also an inverse tyre model representative of a relationship between wheel slip and longitudinal tyre force at different road friction and tyre normal force conditions. The

processing circuitry can then be arranged to determine a longitudinal tyre force generating capability based on the wheel slip, the longitudinal tyre force, and the inverse tyre model. Thus, not only the current longitudinal force of the tyre is determined, but also its force generating capability. This information is again very useful in controlling motion by the heavy-duty vehicle. The force generating capability can, for instance, be used in allocating motion requests between motion actuators of the vehicle, where each motion actuator has a respective actuator capability of generating force.

The present disclosure furthermore relates to a computer system for controlling the motion of a heavy-duty vehicle. The system comprises a tyre belt speed sensor, a vehicle speed sensor, and processing circuitry. The vehicle speed sensor is arranged to determine data indicative of a longitudinal speed of the vehicle relative to a road surface supporting the vehicle. The processing circuitry is arranged to determine a wheel slip associated with the tyre based on the data indicative of the vehicle speed and on the data indicative of the angular speed of the tyre belt. This wheel slip is in many ways more accurate than the wheel slip determined based on the speed of rotation of the wheel rim or wheel axle, since it also accounts for pre-tension in the tyre belt. Thus, dynamic effects involving the resilience of the tyre thread are captured by the wheel slip metric, which is an advantage.

There is also disclosed herein a computer system for determining a longitudinal tyre force associated with at least one wheel comprised in a wheel and drive axle system on a heavy-duty vehicle. The computer system comprises processing circuitry configured to obtain data indicative of an angular speed of a drive axle of the wheel, obtain data indicative of an angular speed of a tyre belt of the wheel, determine a pretension torque of a mechanical system comprising the drive axle and the at least one wheel, in response to an applied torque at the drive axle, and determine the longitudinal tyre force based on the pretension torque and on a pre-determined set of mechanical properties of the at least one wheel and drive axle system. This way longitudinal tyre force can be determined in a reliable manner, which is an advantage.

The different techniques and features of the computer system discussed herein may also be described as corresponding methods, associated with the same advantages. The above aspects, accompanying claims, and/or examples disclosed herein above and later below may be suitably combined with each other as would be apparent to anyone of ordinary skill in the art.

Additional features and advantages are disclosed in the following description, claims, and drawings, and in part will be readily apparent therefrom to those skilled in the art or recognized by practicing the disclosure as described herein. There are also disclosed herein control units, computer systems, computer readable media, and computer program products associated with the above discussed technical benefits.

BRIEF DESCRIPTION OF THE DRAWINGS

With reference to the appended drawings, below follows a more detailed description of aspects of the disclosure cited as examples.

Figure 1 illustrates an example heavy-duty vehicle,

Figure 2 schematically shows an example wheel with a tyre belt speed sensor,

Figures 3A-B schematically illustrate a wheel and a wheel driveline,

Figure 4 shows aspects of an example vehicle control system,

Figures 5A-D show some example general tyre belt speed sensor principles,

Figure 6 is a graph illustrating a relationship between wheel slip and tyre force,

Figure 7 illustrates an example heavy-duty vehicle with tyre belt speed sensors,

Figure 8 is a schematic diagram of an exemplary computer system,

Figures 9A-B are flow charts that illustrate methods, and

Figure 10 shows an example computer program product.

DETAILED DESCRIPTION

The present disclosure will now be described more fully hereinafter with reference to the accompanying drawings, in which exemplary embodiments are shown. The disclosure may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided for thoroughness and completeness. Like reference character refer to like elements throughout the description. Aspects set forth below represent the necessary information to enable those skilled in the art to practice the disclosure.

Figure 1 illustrates an example heavy-duty vehicle 100, here in the form of a truck comprising a tractor 110 and a trailer 120. The tractor 110 of the vehicle 100 comprises two front wheels 101 of a steered front axle and a set of rear wheels 102 on rear tractor axles. The trailer 120 also comprises wheels 103 that support it on the road surface 104, in addition to the trailer support at the tractor fifth wheel. A heavy-duty vehicle may be defined in some cases as a freight vehicle of more than 3.5 tons or as a passenger transport vehicles of more than 8 seats. A heavy-duty vehicle may also be defined as a vehicle with a frontal area that is larger than 45 square feet, which is about 4.18 square meters.

The vehicle 100 comprises a computer-implemented control system arranged to estimate vehicle motion relative to the road surface 104 and/or in a global reference system. The control system implements one or more control functions that control vehicle motion based at least in part on the estimated vehicle motion. This control system may comprise one or more control units 130 distributed over the vehicle or centralized at one place. Each vehicle control unit 130 may comprise one or more processor devices. A processor device may be distributed over several spatially separated units or centralized in one place. The control system, or parts thereof, may be arranged to communicate via wireless link 140 to a wireless access point 150, such as a radio base station of a cellular access network or the like. Thus, the vehicle control system may communicate with one or more remote servers 160 implementing data repositories, remote processing resources, and the like, in order to exchange data and perform various computation tasks. The vehicle control system 130 may be referred to as, or form part of, a system for vehicle motion management (VMM).

Generally, herein, various forms of data signals and messages are transmitted between functions, internal to some processing circuitry or in between physically separated processing devices. These signals and messages are often referred to in terms of data indicative of a given parameter or data item. It is appreciated that the term "data indicative of" is to be construed broadly to mean, e.g., the actual value, an approximation of the value, or an abstraction of the value. The data can for instance be represented using more or less bits in a digital message or transmitted in analog form. A given value may also be represented using an abstraction or code, such as a discrete value from 1-10.

Figure 2 schematically illustrates a driven wheel 200. It is appreciated that both the front wheels 101 and the rear wheels 102 of the tractor can be driven, as well as the wheels on the trailer 120, although self-propelled trailer units are less common. The wheel 200 comprises a tyre 215. The tyre is a ring-shaped resilient component that surrounds a wheel's rim 220 to transfer a vehicle's load from the axle through the wheel to the ground and to provide traction on the surface over which the wheel travels. Most automotive tyres are pneumatically inflated structures, which also provide a flexible cushion that absorbs shock as the tyre rolls over rough features on the road surface 104. The tyre is flexible, which means that it is subject to torsion about the wheel axle as torque is transmitted to it from the road surface or from the drive axle.

The outer peripheral part of the tyre facing the road surface 104 in use will be referred to generally herein as the tyre belt 210, although it is appreciated that the tyre belt is really the supporting structure commonly arranged just underneath the tyre thread. The area of engagement between the road surface 104 and the tyre outer surface is generally referred to as the tyre contact patch, and this is where the tyre force is generated.

Longitudinal tyre force F_x is the force generated along the intersection of the wheel plane and the road surface 104. Lateral tyre force F_y is perpendicular to the longitudinal tyre force and directed along the road surface. Hence, the longitudinal and lateral directions are defined in the local coordinate system of a given wheel, which means that the longitudinal direction changes relative to a global reference system if the wheel is steered. A tyre normal force F_z is normal to the road surface, i.e., substantially vertical in most cases. The present disclosure focuses on determination of tyre longitudinal force F_x, although some aspects of the disclosure also relates to the tyre normal force F_z.

With reference to Figure 2, a driveline is arranged to transfer an actuator torque T_m from a power source 230 such as an electric machine and/or a combustion engine via a gear arrangement 240 associated with a gear ratio i to the wheel rim 220.

The torque T_w applied to the wheel rim 215 is then transferred to the road surface 104 via the tyre 215, whereby a longitudinal tyre force F_x is generated. The power source 230 and associated components are associated with an inertia J_m and the tyre 215 is associated with an inertia J_b. The different inertias in the system is thus assumed to be concentrated at two locations, one is the motor inertia J_m, and the other is the wheel ineria J_b which is assumed to be located around a ring in the tyre belt (hence the subscript "b" for belt). The angular velocity of the drive shaft at the power source 230 is denoted ω_m and the angular velocity of the wheel 200 is denoted ω_b. Most of the discussion herein will evolve around propulsion, i.e., the application of a positive torque T_w applied to the wheel rim 215. However, the discussion and mathematical derivations presented herein can be generalized to also apply to negative applied torques T_w applied to the wheel rim 215, as will be the case if a braking device such as a friction brake is actuated, or if an electric machine is used to apply negative actuator torque T_m instead of positive actuator torque T_m.

The wheel 200 has a radius r, which in the absence of wheel slip means that the angular velocity ω_b of the wheel 200 is related to vehicle velocity v_x as $v_x = \omega_b\, r$. The wheel radius r may be specified as an effective rolling radius of the wheel, or as a nominal radius of the wheel.

Longitudinal tyre force F_x is often estimated from a measured actuator torque T_m by converting the measured actuator torque T_m based on gear ratio i and nominal tyre radius r into tyre force F_x. This approach has its limitations, in particular during transient motion events, i.e., when the vehicle accelerates or decelerates. This is because the relaxation of the tyre 215 is not accounted for. The force pretension of the tyre side wall and tyre thread is neglected which can lead to significant force estimation errors in some cases. The tyre 215 that connects the wheel axle to the road surface 104 in torque transferring relation has a modelled stiffness k_t and damping c_t, which in some cases have significant

effect on the transient response by the tyre to a torque applied at the wheel rim 220. The stiffness k_s and damping c_s of the drive shaft and other components in the driveline from the power source 230 or service brake to the wheel rim 215 are also often neglected, adding to the force estimation error. Other non-rigid components may also add to the force estimation error, such as resilience in the gear arrangement, and in connections between wheel axle and wheel hub.

The effect of the inertia J_b of the tyre is also often neglected which may give large tyre force estimation errors when wheel angular speed is changing. This may become an issue if the wheels on the vehicle are large and heavy, as they normally are in a heavy-duty vehicle such as the vehicle 100 in Figure 1.

The approach to determining longitudinal tyre force F_x proposed herein relies on measuring the output axle speed ω_m at the power source 230, or at least close to the power source 230, e.g., by an axle speed sensor 250, and also the angular velocity ω_b of the tyre belt 210. The output axle speed ω_m of the power source 230 can be determined by a rotary encoder, or by a rotation speed sensor such as a Hall effect sensor or the like. There are two main types of rotary encoder: absolute and incremental. The output of an absolute encoder indicates the current shaft or axle position, making it an angle transducer. The output of an incremental encoder provides information about the rotary motion of the shaft. Both absolute and incremental encoders are well known in the art and will therefore not be discussed in more detail herein. In case the power source 230 is an electric machine, then the output axle speed ω_m is often available as a parameter in the motor controller. An electric machine controller may normally also provide information about the applied actuator torque T_m.

The tyre belt speed ω_b can be determined by a special tyre belt speed sensor 260. The tyre belt speed sensor 260 may, e.g., comprise a radar-based sensor, a vision-based sensor, a vibration pick-up sensor or a roller contact sensor, and will be discussed in more detail below in connection to Figures 5A-D. The tyre belt speed sensor 260 provides an output signal that is indicative of the tyre belt speed ω_b. Both the axle speed sensor 250 and the tyre belt speed sensor 260 provide output signals to the control unit 130.

Having information about the output axle speed ω_m of the power source 230 and the angular velocity ω_b of the tyre belt 210, a model of torque transfer between power source 230 and tyre belt 210 can be used to determine the longitudinal tyre force that is currently generated at the contact patch between a given wheel and the road surface 104. This way the accuracy of the estimated longitudinal tyre force F_x increases, at least in part since some transient effects are now also accounted for.

There may be various actuators connected to single wheel or wheel axle. Dependent on the mechanical connections between actuators and the wheel, the model parameters, e.g., stiffnesses etc., may need to

be adapted individually to each actuator. The parameters can be estimated online, e.g., by probing torque to wheels and measuring the response of the system using an accelerometer. The parameters can also be estimated off-line, e.g., by tuning in a workshop or laboratory, or by measuring rotational torsion and belt force at the wheel in response to an applied actuator torque.

There may be more than one actuator connected to each wheel, e.g., a friction brake and an electrical machine with braking capability. The model can be expanded to cover an arbitrary number of actuators in a straight-forward manner.

There may be more than one wheel actuated by a given power source or brake. The model can also be expanded to cover an arbitrary number of wheels for a given actuator in a straight-forward manner.

There may be more measurements of speeds in the system, e.g., wheel encoder measuring the angular speed of the rim. The model can be expanded to support additional speed sensors in a straightforward manner. If also the rim speed is measured, it is possible to estimate tension of the drive shaft and of the tyre separately, which is an advantage.

With reference also to the schematic illustration of the drive line and wheel system 300 in Figures 3A-B, suppose that an actuator system 310 with inertia J_m is providing an output drive axle torque T_m to the wheel through a gear arrangement 320 with gear ratio i. The shaft angle after the power source 230 is denoted θ_m. The shaft angle can be measured by a rotary encoder 250 or obtained directly from the control circuitry of an electric machine. However, as will be seen in the following, there is no need to actually measure the shaft angle θ_m in absolute terms.

The shaft angle after the gear arrangement 320 is denoted θ_g and the applied torque on the output from the gear arrangement 320 is denoted T_g, respectively. The angle of the tyre belt is denoted by θ_b. These angles may be defined as an angular displacement of the axle and tyre belt in relation to some reference direction, such as a horizontal axis or vertical axis. The time derivative of the angles correspond to the angular speeds, i.e., $\dot{\theta}_b = \omega_b$ and $\dot{\theta}_m = \omega_m$. Angular acceleration is denoted $\ddot{\theta}_b$ and $\ddot{\theta}_m$, respectively.

At least the tyre side wall and the drive shaft are resilient objects, i.e., somewhat elastic, and since they are connected in series, they can be considered as one lumped element 330 with a stiffness k and damping d. This is possible since we here have neglected the inertia of the tyre rim 220, and instead consider all inertia to be located as a ring around the tyre belt 215, which is normally a good approximation, at least in a heavy-duty vehicle such as the vehicle 100. A wheel with tyre radius r and a tyre belt with inertia J_b is connected to the vehicle body with mass m. The velocity of the vehicle in longitudinal direction is denoted v_x, this velocity must be translated into the wheel local coordinate system if it is to be compared to the tyre belt speed ω_b. Losses due to air drag etc. are denoted by F_L in

Figures 3A-B. Accounting for these losses is not strictly necessary, but an improved accuracy will be obtained if they are accounted for, at least approximatively.

The actuator angular speed $\dot{\theta}_m$ can be measured by a rotary encoder or shaft speed sensor as discussed above, and the tangential belt speed $v_b = v_x$ (in the coordinate system of the wheel) if no tyre slip is assumed. Thus, without slip, the vehicle speed is scaled by the tyre belt angular belt speed such that $v_x = r \cdot \dot{\theta}_b$, at least approximately.

A state vector $\boldsymbol{x} = [x_1, x_2, x_3]$ can be used to represent the system 300, where

$$x_1 = \frac{1}{i} \cdot \theta_m - \theta_b$$

$$x_2 = \dot{\theta}_m$$

$$x_3 = \dot{\theta}_b$$

Here, x_1 represents the combined pretention of the drive shaft and the tyre side wall, x_2 is associated with the power source shaft angular speed ω_m and x_3 is associated with the tyre belt angular speed ω_b.

A system model can now be set up for the system 300. This system model may, e.g., be formulated as

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{i} & -1 \\ -\frac{k}{J_m \cdot i} & -\frac{d}{J_m \cdot i^2} & \frac{d}{J_m \cdot i} \\ \frac{k}{(J_b + m \cdot r^2)} & \frac{d}{(J_b + m \cdot r^2) \cdot i} & \frac{-d}{(J_b + m \cdot r^2)} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{J_m} \\ 0 \end{bmatrix} \cdot T_m$$

or in more compact form as

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}T_m$$

where

$$\boldsymbol{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix}$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & \frac{1}{i} & -1 \\ -\frac{k}{J_m \cdot i} & -\frac{d}{J_m \cdot i^2} & \frac{d}{J_m \cdot i} \\ \frac{k}{(J_b + m \cdot r^2)} & \frac{d}{(J_b + m \cdot r^2) \cdot i} & \frac{-d}{(J_b + m \cdot r^2)} \end{bmatrix}$$

$$\boldsymbol{B} = \begin{bmatrix} 0 \\ \frac{1}{J_m} \\ 0 \end{bmatrix}$$

In case losses F_L such as friction, air drag and rolling resistance are also considered, then the system model becomes

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{i} & -1 \\ -\frac{k}{J_m \cdot i} & -\frac{d}{J_m \cdot i^2} & \frac{d}{J_m \cdot i} \\ \frac{k}{(J_b + m \cdot r^2)} & \frac{d}{(J_b + m \cdot r^2) \cdot i} & \frac{-d}{(J_b + m \cdot r^2)} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{J_m} \\ 0 \end{bmatrix} \cdot T_m + \begin{bmatrix} 0 \\ 0 \\ \frac{-r}{(J_w + m \cdot r^2)} \end{bmatrix} \cdot F_L$$

or in more compact form

$$\dot{\boldsymbol{x}} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{B}T_m + \boldsymbol{E}F_L$$

where $\boldsymbol{A}$ and $\boldsymbol{B}$ are as above, and where

$$\boldsymbol{E} = \begin{bmatrix} 0 \\ 0 \\ \frac{-r}{(J_w + m \cdot r^2)} \end{bmatrix}$$

The angular velocities ω_m and ω_w are obtained from the drive shaft speed sensor 250 and from the tyre belt speed sensor 260, and relate to the state vector as

$$\begin{bmatrix} \omega_m \\ \omega_w \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix}$$

which can be written in compact form as

$$\boldsymbol{y} = \boldsymbol{C}\boldsymbol{x}$$

where

$$\boldsymbol{C} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The measurements of the state variables x_1 and x_2 and the process model can now be used to estimate the pretention x_3 that is not directly measurable, at least not with this sensor set-up.

A standard filter can be used to estimate the pretention variable x_3 over time, such as a Kalman filter, and extended Kalman filter, a particle filter or a Luenberger observer structure, which are all well known in the art and will therefore not be discussed in more detail herein. The measured actuator torque T_m is used to parameterize the process equation and used as input to the filter structures. The output from the filter is an estimate of the state vector $\boldsymbol{x}$, which among other things comprises the pretention variable x_3.

The longitudinal tyre force F_x can now be found by using the estimates x_1 and x_3 along with their respective time derivatives. By Newtons second law, and the relationships illustrated in Figure 2, the tyre belt inertia J_b multiplied by the angular tyre belt acceleration $\ddot{\theta}_b$ should equal the difference between pretention torque $d\dot{x}_1 + kx_1$ and tyre force F_x multiplied by tyre radius r, at least in the absence of measurement noise, i.e.,

$$J_b\ddot{\theta}_b = d\dot{x}_1 + kx_1 - r \cdot F_x$$

The following estimator of longitudinal tyre force F_x is thus obtained

$$\hat{F}_x = \frac{d\dot{x}_1 + kx_1 - J_b\dot{x}_3}{r}$$

where $\hat{F}_x$ denotes an estimate of F_x.

Another model which can be used in a similar function is one where the states are given by

$$x_1 = \frac{1}{i}\theta_m - \theta_r$$
$$x_2 = \theta_r - \theta_b$$
$$x_3 = \dot{\theta}_m$$
$$x_4 = \dot{\theta}_r$$
$$x_5 = \dot{\theta}_b$$

where θ_r is wheel rim angle. The system model then becomes

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\end{bmatrix}=\begin{bmatrix}0 & 0 & \frac{1}{i} & -1 & 0\\ 0 & 0 & 0 & 1 & -1\\ -\frac{k_s}{J_m i} & 0 & -\frac{d_s}{J_m i} & \frac{d_s}{J_m i} & 0\\ \frac{k_s}{J_r} & -\frac{k_t}{J_r} & \frac{d_s}{J_r} & -\frac{(d_s+d_t)}{J_r} & \frac{d_t}{J_r}\\ 0 & \frac{k_t}{J_b} & 0 & \frac{d_t}{J_b} & -\frac{d_t}{J_b}\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\end{bmatrix}+\begin{bmatrix}0 & 0\\ 0 & 0\\ \frac{1}{J_m} & 0\\ 0 & \frac{1}{J_r}\\ 0 & 0\end{bmatrix}\begin{bmatrix}T_m\\ T_b\end{bmatrix}+\begin{bmatrix}0\\ 0\\ 0\\ 0\\ -\frac{r}{J_b}\end{bmatrix}F_x$$

where J_r is the wheel rim inertia and T_b is friction brake torque, and where the stiffness and damping in the system have been divided up as k_s, k_t and d_s, d_t. The output from the sensor arrangement is

$$\begin{Bmatrix}\dot{\theta}_m\\ \dot{\theta}_r\\ \dot{\theta}_b\end{Bmatrix}=\begin{bmatrix}0 & 0 & 1 & 0 & 0 & 0\\ 0 & 0 & 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 0 & 1 & 0\end{bmatrix}\begin{Bmatrix}x_1\\ x_2\\ x_3\\ x_4\\ x_5\\ x_6\end{Bmatrix}$$

It is, however, noted that this model is parameterized by the tyre force F_x, the motor torque T_m, and a friction brake torque T_b.

To summarize, with reference also to Figure 8 that will be discussed in more detail below, there is disclosed herein a computer system 130, 800 for controlling motion of a heavy-duty vehicle 100. The system comprises at least one tyre belt speed sensor 260 with a corresponding axle speed sensor 250 and processing circuitry. A tyre belt speed sensor is a sensor that is configured to sense motion of an outer surface of a tyre 215, preferably the part of the tyre 215 that engages the road surface 104 in use. The tyre belt speed sensor is useful for many things, among which is to provide data on the tyre belt speed ω_b. Some example tyre belt speed sensors will be discussed in more detail below in connection to Figures 5A-D. The axle speed sensor 250 is arranged to determine an angular speed ω_m of a drive axle associated with a wheel 101, 102, 103 of the heavy-duty vehicle 100 that supports the tyre 215. This sensor outputs data indicative of the angular speed ω_m of the drive axle on an axle speed sensor output port. It is appreciated that the axle speed sensor output port and/or the output port of the tyre belt speed sensor that is arranged to output data indicative of the angular speed ω_b of the tyre belt 210 may be internal to the computer system 130, 800 or external to the computer system, i.e., connected to the computer system 130, 800 by wire or wireless interface. Together, the tyre belt speed sensor and the axle speed sensor provide the input $\boldsymbol{y} = \boldsymbol{Cx}$ discussed above, which is thus available to the processing circuitry. The processing circuitry is arranged to determine the longitudinal tyre force F_x associated with the wheel 101, 102, 103 based on the data indicative of the angular speed ω_m of the drive axle and

based on the data indicative of the angular speed ω_b of the tyre belt 210, e.g., by using the methods discussed above or an alternative method in line with the general discussions herein.

There is also disclosed herein a computer system 130, 800 for determining a longitudinal tyre force F_x associated with at least one wheel 101, 102, 103, 200 comprised in a wheel and drive axle system 300 on a heavy-duty vehicle 100. The computer system 130, 800 comprises processing circuitry configured to obtain data indicative of an angular speed ω_m of a drive axle of the wheel 101, 102, 103, 200, obtain data indicative of an angular speed ω_b of a tyre belt 210 of the wheel 101, 102, 103, 200, determine a pretension torque x_1 of a mechanical system comprising the drive axle and the at least one wheel, in response to an applied torque T_m at the drive axle, and also determine the longitudinal tyre force F_x based on the pretension torque x_1 and on a pre-determined set of mechanical properties of the at least one wheel and drive axle system 300. The set of mechanical properties of the at least one wheel and drive axle system 300 may comprise a lumped stiffness coefficient k and a lumped damping coefficient d of the wheel and drive axle system 300, as illustrated in Figure 3B. The stiffness and damping in the mechanical system may also be divided up into more than one component and modelled accordingly.

Figure 4 schematically illustrates functionality 400 for controlling the vehicle 100 by some example motion support devices (MSD) here comprising brake actuators, propulsion actuators, and power steering, with respective controllers collectively referred to herein as MSD control 430. A traffic situation management (TSM) function 410 plans driving operation with a time horizon of 10 seconds or so. This time period corresponds to, e.g., the time it takes for the vehicle 100 to negotiate a curve or the like. The vehicle maneuvers, planned and executed by the TSM function 410, can be associated with acceleration profiles a_{req} and curvature profiles c_{req} which describe a desired target vehicle velocity in the vehicle forward direction and turning to be maintained for a given maneuver. The TSM function continuously requests the desired acceleration profiles a_{req} and steering angles (or curvature profiles c_{req}) from the VMM system 420 which performs force allocation to meet the requests from the TSM function in a safe and robust manner.

Each wheel 101, 102, 103 on the vehicle 100 has a longitudinal velocity component v_x and a lateral velocity component v_y (in the coordinate system of the wheel or in the coordinate system of the vehicle, depending on implementation). There is a longitudinal tyre force F_x and a lateral tyre force F_y, and also a normal force F_z acting on the wheel. Unless explicitly stated otherwise, the tyre forces are defined in the coordinate system of the wheel, i.e., the longitudinal force is directed in the rolling plane of the wheel, while the lateral tyre force is directed normal to the rolling plane of the wheel.

The TSM function 410 generates vehicle motion requests which may comprise a desired curvature c_{req} to be followed by the vehicle, and desired vehicle unit accelerations a_{req}. Given the discussion above, it

is appreciated that the motion request will have an impact on the expected nominal difference in tyre rotary motion.

The VMM system 420 operates with a time horizon of about 1 second or so, and continuously transforms the acceleration profiles a_{req} and curvature profiles c_{req} from the TSM function 410 into control commands 431, 432, 433 for controlling vehicle motion functions, actuated by the different MSDs of the vehicle 100 which report back capabilities 434, 435, 436 to the VMM function 420, which in turn may be used as constraints in the vehicle control. One example such constraint may be the maximum achievable longitudinal tyre force as discussed in connection to Figure 6. The VMM system 420 performs vehicle state or motion estimation 450, i.e., the VMM system 420 continuously determines a vehicle state **s** as function of time t comprising positions, speeds, accelerations, and articulation angles of the different units in the vehicle combination by monitoring operations using various sensors 440 arranged on the vehicle 100, often but not always in connection to the MSDs. An important input to the state estimation 450 may of course be the signals from the vehicle speed sensor and the wheel speed sensors on the heavy-duty vehicle 100, as well as the signals from one or more tyre belt speed sensors 260 on the vehicle. The vehicle state at a future time instant can also be predicted by a state prediction function 455. This vehicle state prediction function may be realized by a vehicle model having a vehicle state which can be extrapolated into a predicted vehicle state, given a current vehicle state, and optionally also given the current vehicle motion request.

The result of the state estimation 450 and optionally also the state prediction 455, i.e., the estimated vehicle state **s** at one or more time instants, is input to a force generation module 460 which determines the required global forces $\mathbf{V}=[V_1, V_2]$ for the different vehicle units to cause the vehicle 100 to move according to the requested acceleration and curvature profiles a_{req}, c_{req}, and to behave according to the desired vehicle behavior. This example has two vehicle units. More vehicle units are possible, and also a single vehicle unit, e.g., in case the vehicle is a rigid truck or a passenger car. The required global force vector **V** is input to an MSD coordination function 470 which allocates tyre forces and coordinates other MSDs such as steering and suspension. The coordination by the MSD coordination function is advantageously performed by taking the longitudinal tyre force generating capabilities of the different wheels into account. This information can be obtained from the tyre force monitor function or be determined based on data received from the tyre force monitor function 480. The state estimation function may also benefit from input data from the tyre force monitoring function 480, regarding longitudinal tyre force at the different tyres for instance.

The MSD coordination function outputs an MSD control allocation for the i:th wheel, which may comprise any of a torque T_i, a longitudinal wheel slip λ_i, a wheel rotational speed ω_i, and/or a wheel

steering angle δ_i. The MSD coordination function may, e.g., be realized using a mathematical optimization problem solver which finds a control allocation that fulfils the global force requirements and at the same time does not allocate a motion request to some MSD that it cannot fulfil. Several MSD coordination functions have been described previously in the literature. MSD coordination functions will therefore not be discussed in more detail herein. The coordinated MSDs then together provide the desired lateral Fy and longitudinal Fx forces on the vehicle units, as well as the required moments Mz, to obtain the desired motion by the vehicle combination 100. Thus, according to some aspects of the present disclosure, the VMM system 420 manages both force generation and MSD coordination, i.e., it determines what forces that are required at the vehicle units in order to fulfil the requests from the TSM function 410, for instance to accelerate the vehicle according to a requested acceleration profile requested by TSM and/or to generate a certain curvature motion by the vehicle also requested by TSM. The forces may comprise e.g., yaw moments Mz, longitudinal forces Fx and lateral forces Fy, as well as different types of torques to be applied at different wheels. The forces are determined such as to generate the vehicle behavior which is expected by the TSM function in response to the control inputs generated by the TSM function 410.

Figures 5A-D illustrate some general principles of tyre belt speed sensors 260 for use with heavy-duty vehicles, such as the vehicle 100 illustrated in Figure 1. Figure 5A schematically illustrates a tyre belt speed sensor 260 for a heavy-duty vehicle 100. The sensor 260 comprises a sensor front end 510 configured to sense 515 motion of an outer surface of a tyre 215, i.e., the part of the tyre 215 that is arranged to engage the road surface 104 supporting the heavy-duty vehicle 100 in use. It is preferred that the tyre belt speed sensor 260 is configured to sense a motion of the tyre thread part of the tyre 215, but relevant data can also be obtained from a sensor configured to sense a motion of the outer side walls of the tyre. For instance, a roller wheel arrangement can be arranged to engage the side of the tyre, like a dynamo on a bicycle tyre. Magnets can also be embedded into the tyre side wall and detected as they pass a Hall effect sensor or the like. A sensor back end 520 is configured to determine data indicative of an angular speed ω_b of the tyre belt 210 of the tyre 215 based on the motion sensed by the sensor front end 510, while an output port 530 is arranged to output the data indicative of the angular speed ω_b of the tyre belt 210, e.g., to the control unit 130 or to some other processing device.

Figure 5B illustrates two example tyre belt speed sensor principles. According to a first example principle, the sensor front end 510 comprises a vision-based sensor 540 arranged to capture a sequence of images of the outer surface of the tyre 215 at respective image capture time instants. In this case the sensor back end 520 is configured to determine the data indicative of the angular speed ω_b based on a comparison of the images in the captured sequence of images and on the respective image capture time

instants. The sensor back-end may, e.g., implement a correlation function that determines how far the tyre thread pattern has shifted from one image in the sequence to the next, from which shift distance the tyre belt speed can be determined, as long as the time in between images is at least approximately known. The sensor back-end may of course implement a filter also to suppress noise, and to average over a number of images in the sequence. The vision-based sensor can be a camera of low resolution, and possibly only a binary color image capture element, i.e., a black and white camera sensor. The camera sensor may not work efficiently under dark operating conditions and may need a light to complement it in order to operate efficiently during night and in other dark operating conditions.

Figure 5B also illustrates an example tyre belt speed sensor, where the sensor front end 510 comprises a Hall effect sensor 580 arranged to detect passage of a plurality of magnets 585 attached to or embedded in the outer part of the tyre 215.The sensor back end 520 is here configured to determine the data indicative of the angular speed ω_b based on the frequency of detected passages by the Hall effect sensor 580 and on data associated with a tangential distance between the plurality of magnets 585. The data associated with a tangential distance between the plurality of magnets 585 may be a preconfigured value or determined by a calibration operation involving input from an external travelled distance sensor or vehicle speed sensor.

In Figure 5C, the sensor front end 510 comprises a radar transceiver 550 with a bore-sight direction B arranged pointing at the outer surface of the tyre 215 at an angle α relative to a radial direction D of the tyre 215. The sensor back end 520 is in this case configured to determine the data indicative of the angular speed ω_b based on a Doppler shift of radar signal backscatter received from the tyre 215.

Figure 5D illustrates two example tyre belt speed principles. In the first example the sensor front end 510 comprises a roller wheel arrangement 560 arranged in use to engage the tyre in rolling contact 565. In this case the sensor back end 520 is configured to determine the data indicative of the angular speed ω_b based on a measured rotation speed of the roller wheel arrangement 560. The roller wheel arrangement may be configured to engage the radial outer part of the tyre side wall instead of the tyre thread, which gives less disturbance from the tyre thread.

An example where the sensor front end 510 comprises a vibration pick-up member 570 arranged in use to engage the outer surface of the tyre 215 is also shown in Figure 5D. In this case the sensor back end 520 is configured to determine the data indicative of the angular speed ω_b based on a vibration of the vibration pick-up member 570 and on data associated with a tyre thread pattern of the tyre 215.

The sensor back end 520 is optionally also configured to detect a tyre explosion of the tyre 215 based on a detected disturbance in the sensed motion of the outer surface of the tyre 215. Any of the tyre belt

speed sensor principles can be used for this additional purpose. A tyre explosion normally causes significant deformation of the outer surface of the tyre 215. Hence, if the sensor front end 510 outputs a signal indicative of great disturbance, then a tyre explosion may have occurred.

Longitudinal wheel slip $\lambda_{x,i}$ for the i-th wheel on the vehicle 100 may, in accordance with SAE J370 (SAE Vehicle Dynamics Standards Committee January 24, 2008) be defined as

$$\lambda_x = \frac{r\,\omega_b - v_x}{max(|r\,\omega_b|, |v_x|)} = \frac{v_b - v_x}{max(|v_b|, |v_x|)}$$

The wheel slip λ_x is bounded between -1 and 1 and quantifies how much the wheel is slipping with respect to the road surface 104. Wheel slip is, in essence, a speed difference measured between the tyre belt tangential speed and the vehicle but normalized with speed.

If wheel slip λ_x is considered, then the relationship $v_x = r \cdot \dot{\theta}_b$ no longer holds with equality. This can be solved by adding another state $x_4 = v_x$ to the state vector $\boldsymbol{x}$ and also adding a model that defines wheel slip and relates it to the other state variables. Since definition of slip is non-linear with respect to the states belt angular speed and vehicle speed, the system will then become non-linear. This can be solved by, for example using an extended Kalman filter (EKF) and linearizing the system around an operation point.

The angular velocity of the wheel rim 220 is often used to determine wheel slip since it can be sensed by a wheel speed sensor in an efficient and reliable manner. However, this requires the effective rolling radius r of the wheel to be known, which is not always the case, since it changes with, e.g., temperature of the tyre, tyre wear, tyre inflation pressure, and wheel normal load. Using the wheel rim rotation speed also fails to account for transients in wheel slip due to the relaxation of the tyre side wall and tyre thread which are not rigid objects, but subject to deformation. By using the tyre belt speed, as sensed by a tyre belt speed sensor, instead of wheel rim speed, more accurate wheel slip data is obtained which is also independent of wheel radius, and therefore not affected by inaccuracies in wheel radius data.

Figure 6 is a graph showing an example 600 of achievable tyre force as function of longitudinal wheel slip. F_x is the longitudinal tyre force while F_y is the maximum obtainable lateral tyre force for a given wheel slip. This type of relationship between wheel slip and generated tyre force is often referred to as an inverse tyre model, and it is generally known. Since the tyre characteristics are not monotonically growing for larger slip values, the inverse tyre model does not exist for all slip values. Therefore, the inverse is normally taken from zero force up to the peak force. The examples in Figure 6 are for positive tyre forces, i.e., acceleration. Similar relationships exist between wheel slip and negative tyre force, i.e., braking. The relationship is approximately linear in a region 610 below some wheel slip threshold value, and then exhibits non-linearity in the region 620.

The maximum obtainable longitudinal tyre force F_x is bounded by the product of the road friction coefficient μ and the wheel normal force F_z. Hence, if either friction or normal force or both decrease, the force generating capability of the wheel also decreases. This is illustrated in Figure 6 by the three curves 630, 640 and 650, where $\mu_1 F_{z1} > \mu_2 F_{z2} > \mu_3 F_{z3}$. Given an estimate of the current longitudinal tyre force $\hat{F}_x$ that is generated by a wheel, along with a current wheel slip value λ_x, the product of friction and normal force can be determined, and thus also the longitudinal force generating capability of the wheel. For instance, a set of different inverse tyre models 630, 640, 650 can be stored in memory. A pair $\{\lambda_x, \hat{F}_x\}$ can then be compared to the set of stored inverse models and the best fit selected. It is also possible to store an inverse tyre model that is parameterized by the product of friction and normal force instead of a set of discrete inverse tyre models.

Thus, it is appreciated that the processing circuitry discussed above is optionally arranged to obtain data indicative of a wheel slip λ_x associated with the tyre 215, and an inverse tyre model 600 representative of a relationship between wheel slip and longitudinal tyre force at different road friction μ and tyre normal force F_x conditions, and to determine a longitudinal tyre force F_x generating capability based on the wheel slip λ_x, the longitudinal tyre force F_x, and the inverse tyre model 600. Since it is now possible to determine the longitudinal tyre force F_x including dynamics, it also becomes possible to determine wheel slip including dynamics, which is an advantage.

In case the system has access to vehicle speed data, e.g., from a vehicle speed sensor arranged to determine data indicative of a longitudinal speed v_x of the vehicle 100 relative to a road surface 104 supporting the vehicle 100, then the processing circuitry can be arranged to determine a wheel slip λ_x associated with the tyre 215 based on the data indicative of the vehicle speed v_x and on the data indicative of the angular speed ω_b of the tyre belt 210. This wheel slip is then determined independently of any errors in wheel radius information available to the processing circuitry, which is an advantage. The wheel slip determined based on tyre belt speed also accounts for transient effects due to elasticity in the tyre, which is an advantage.

Figure 7 illustrates a heavy-duty vehicle where tyre belt speed sensors 260 have been arranged in connection to several of the wheels on the vehicle 100. The control unit 130 is configured to determine a respective tyre force $\{F_{x,1}, F_{x,2}, F_{x,3}, F_{x,4}, F_{x,5}, F_{x,6}\}$ for each of the wheels comprising a tyre belt speed sensor. This data is of course very useful in a heavy-duty VMM system such as the system 400 discussed above. The control unit 130 may of course also be configured to determine tyre force generating capability, and also detect tyre explosion by using the plurality of tyre belt speed sensors 260 on the heavy-duty vehicle.

Figure 8 is a schematic diagram of a computer system 800 for implementing examples disclosed herein. The computer system 800 is adapted to execute instructions from a computer-readable medium to perform these and/or any of the functions or processing described herein. The computer system 800 may be connected (e.g., networked) to other machines in a LAN, an intranet, an extranet, or the Internet. While only a single device is illustrated, the computer system 800 may include any collection of devices that individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein. Accordingly, any reference in the disclosure and/or claims to a computer system, computing system, computer device, computing device, control system, control unit, electronic control unit (ECU), processor device, etc., includes reference to one or more such devices to individually or jointly execute a set (or multiple sets) of instructions to perform any one or more of the methodologies discussed herein. For example, a control system may include a single control unit, or a plurality of control units connected or otherwise communicatively coupled to each other, such that any performed function may be distributed between the control units as desired. Further, such devices may communicate with each other or other devices by various system architectures, such as directly or via a Controller Area Network (CAN) bus, etc.

The computer system 800 may comprise at least one computing device or electronic device capable of including firmware, hardware, and/or executing software instructions to implement the functionality described herein. The computer system 800 may include a processor device 802 (may also be referred to as a control unit), a memory 804, and a system bus 806. The computer system 800 may include at least one computing device having the processor device 802. The system bus 806 provides an interface for system components including, but not limited to, the memory 804 and the processor device 802. The processor device 802 may include any number of hardware components for conducting data or signal processing or for executing computer code stored in memory 804. The processor device 802 (e.g., control unit) may, for example, include a general-purpose processor, an application specific processor, a Digital Signal Processor (DSP), an Application Specific Integrated Circuit (ASIC), a Field Programmable Gate Array (FPGA), a circuit containing processing components, a group of distributed processing components, a group of distributed computers configured for processing, or other programmable logic device, discrete gate or transistor logic, discrete hardware components, or any combination thereof designed to perform the functions described herein. The processor device may further include computer executable code that controls operation of the programmable device.

The system bus 806 may be any of several types of bus structures that may further interconnect to a memory bus (with or without a memory controller), a peripheral bus, and/or a local bus using any of a variety of bus architectures. The memory 804 may be one or more devices for storing data and/or

computer code for completing or facilitating methods described herein. The memory 804 may include database components, object code components, script components, or other types of information structure for supporting the various activities herein. Any distributed or local memory device may be utilized with the systems and methods of this description. The memory 804 may be communicably connected to the processor device 802 (e.g., via a circuit or any other wired, wireless, or network connection) and may include computer code for executing one or more processes described herein. The memory 804 may include non-volatile memory 808 (e.g., read-only memory (ROM), erasable programmable read-only memory (EPROM), electrically erasable programmable read-only memory (EEPROM), etc.), and volatile memory 810 (e.g., random-access memory (RAM)), or any other medium which can be used to carry or store desired program code in the form of machine-executable instructions or data structures, and which can be accessed by a computer or other machine with a processor device 802. A basic input/output system (BIOS) 812 may be stored in the non-volatile memory 808 and can include the basic routines that help to transfer information between elements within the computer system 800.

The computer system 800 may further include or be coupled to a non-transitory computer-readable storage medium such as the storage device 814, which may comprise, for example, an internal or external hard disk drive (HDD) (e.g., enhanced integrated drive electronics (EIDE) or serial advanced technology attachment (SATA)), HDD (e.g., EIDE or SATA) for storage, flash memory, or the like. The storage device 814 and other drives associated with computer-readable media and computer-usable media may provide non-volatile storage of data, data structures, computer-executable instructions, and the like.

A number of modules can be implemented as software and/or hard coded circuitry to implement the functionality described herein in whole or in part. The modules may be stored in the storage device 814 and/or in the volatile memory 810, which may include an operating system 816 and/or one or more program modules 818. All or a portion of the examples disclosed herein may be implemented as a computer program product 820 stored on a transitory or non-transitory computer-usable or computer-readable storage medium (e.g., single medium or multiple media), such as the storage device 814, which includes complex programming instructions (e.g., complex computer-readable program code) to cause the processor device 802 to carry out the steps described herein. Thus, the computer-readable program code can comprise software instructions for implementing the functionality of the examples described herein when executed by the processor device 802. The processor device 802 may serve as a controller or control system for the computer system 800 that is to implement the functionality described herein.

The computer system 800 also may include an input device interface 822 (e.g., input device interface and/or output device interface). The input device interface 822 may be configured to receive input and selections to be communicated to the computer system 800 when executing instructions, such as from a keyboard, mouse, touch-sensitive surface, etc. Such input devices may be connected to the processor device 802 through the input device interface 822 coupled to the system bus 806 but can be connected through other interfaces such as a parallel port, an Institute of Electrical and Electronic Engineers (IEEE) 1394 serial port, a Universal Serial Bus (USB) port, an IR interface, and the like. The computer system 800 may include an output device interface 824 configured to forward output, such as to a display, a video display unit (e.g., a liquid crystal display (LCD) or a cathode ray tube (CRT)). The computer system 800 may also include a communications interface 816 suitable for communicating with a network as appropriate or desired.

Figures 9A-B are flow charts that illustrate methods which correspond to the different technical features of the computer system and the vehicles discussed herein. The flow chart in Figure 9A illustrates a computer-implemented method, performed by a computer system 130, 800, for sensing a rotational motion of a tyre 215 on a heavy-duty vehicle 100. The method comprises:

providing Sa1 a sensor front end 510 configured to sense 515 motion of an outer surface of the tyre 215, where the outer surface of the tyre 215 is arranged to engage a road surface 104 supporting the heavy-duty vehicle 100 in use,

providing Sa2 a sensor back end 520 configured to determine data indicative of an angular speed ω_b of a tyre belt 210 of the tyre 215 based on the motion sensed by the sensor front end 510, and

determining Sa3 the rotational motion of the tyre 215 by the sensor back end 520 as the angular speed ω_b of the tyre belt 210 of the tyre 215.

According to some aspects, the method further comprises monitoring Sa4 the rotational motion of the tyre 215 and detecting a tyre explosion based on a disturbance in the monitored rotational motion by the tyre 215.

The flow chart in Figure 9B illustrates a computer-implemented method, performed by a computer system 130, 800, for controlling motion of a heavy-duty vehicle 100 comprising a wheel 101, 102, 103, 200 that supports a tyre 215. The method comprises:

providing Sb1 at least one tyre belt speed sensor 260 and at least one axle speed sensor 250,

determining Sb2 an angular speed ω_m of a drive axle associated with the wheel 101, 102, 103, 200 by the axle speed sensor 250,

determining Sb3 and angular speed ω_b of a tyre belt 210 associated with the wheel 101, 102, 103, 200 by the tyre belt speed sensor 260, and

determining Sb4 a longitudinal tyre force F_x associated with the wheel 101, 102, 103, 200 based on the angular speed ω_m of the drive axle and based on the angular speed ω_b of the tyre belt 210.

According to some aspects, the method further comprises obtaining Sb5 data indicative of a wheel slip λ_x associated with the tyre 215, and an inverse tyre model 600 representative of a relationship between wheel slip and longitudinal tyre force at different road friction μ and tyre normal force F_x conditions, and determining Sb6 a longitudinal tyre force F_x generating capability of the wheel based on the wheel slip λ_x, the longitudinal tyre force F_x, and the inverse tyre model 600.

Figure 10 illustrates a computer readable medium 1010 carrying a computer program comprising program code means 1020 for performing the methods illustrated in Figure 9 and the techniques discussed herein, when said program product is run on a computer. The computer readable medium and the code means may together form a computer program product 1000.

The operational steps described in any of the exemplary aspects herein are described to provide examples and discussion. The steps may be performed by hardware components, may be embodied in machine-executable instructions to cause a processor to perform the steps, or may be performed by a combination of hardware and software. Although a specific order of method steps may be shown or described, the order of the steps may differ. In addition, two or more steps may be performed concurrently or with partial concurrence.

The terminology used herein is for the purpose of describing particular aspects only and is not intended to be limiting of the disclosure. As used herein, the singular forms "a," "an," and "the" are intended to include the plural forms as well, unless the context clearly indicates otherwise. As used herein, the term "and/or" includes any and all combinations of one or more of the associated listed items. It will be further understood that the terms "comprises," "comprising," "includes," and/or "including" when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.

It will be understood that, although the terms first, second, etc., may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element without departing from the scope of the present disclosure.

Relative terms such as "below" or "above" or "upper" or "lower" or "horizontal" or "vertical" may be used herein to describe a relationship of one element to another element as illustrated in the Figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the Figures. It will be understood that when an element is referred to as being "connected" or "coupled" to another element, it can be directly connected or coupled to the other element, or intervening elements may be present. In contrast, when an element is referred to as being "directly connected" or "directly coupled" to another element, there are no intervening elements present.

Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.

It is to be understood that the present disclosure is not limited to the aspects described above and illustrated in the drawings; rather, the skilled person will recognize that many changes and modifications may be made within the scope of the present disclosure and appended claims. In the drawings and specification, there have been disclosed aspects for purposes of illustration only and not for purposes of limitation, the scope of the inventive concepts being set forth in the following claims.

CLAIMS

1. A tyre belt speed sensor (260) for a heavy-duty vehicle (100), the sensor (260) comprising

a sensor front end (510) configured to sense (515) motion of an outer surface of a tyre (215), where the outer surface of the tyre (215) is arranged to engage a road surface (104) supporting the heavy-duty vehicle (100) in use,

a sensor back end (520) configured to determine data indicative of an angular speed (ω_b) of a tyre belt (210) of the tyre (215) based on the motion sensed by the sensor front end (510), and

an output port (530) arranged to output the data indicative of the angular speed (ω_b) of the tyre belt (210).

2. The tyre belt speed sensor (260) according to claim 1, where the sensor front end (510) comprises a vision-based sensor (540) arranged to capture a sequence of images of the outer surface of the tyre (215) at respective image capture time instants, where the sensor back end (520) is configured to determine the data indicative of the angular speed (ω_b) based on a comparison of the images in the captured sequence of images and on the respective image capture time instants.

3. The tyre belt speed sensor (260) according to claim 1 or 2, where the sensor front end (510) comprises a radar transceiver (550) with a bore-sight direction (B) arranged in use to point at the outer surface of the tyre (215) at an angle (α) relative to a radial direction (D) of the tyre (215), where the sensor back end (520) is configured to determine the data indicative of the angular speed (ω_b) based on a Doppler shift of radar signal backscatter received from the tyre (215).

4. The tyre belt speed sensor (260) according to any previous claim, where the sensor front end (510) comprises a roller wheel arrangement (560) arranged in use to engage the tyre in rolling contact (565), where the sensor back end (520) is configured to determine the data indicative of the angular speed (ω_b) based on a measured rotation speed of the roller wheel arrangement (560).

5. The tyre belt speed sensor (260) according to any previous claim, where the sensor front end (510) comprises a vibration pick-up member (570) arranged in use to engage the outer surface of the tyre (215), where the sensor back end (520) is configured to determine the data indicative of the angular speed (ω_b) based on a vibration of the vibration pick-up member (570) and on data associated with a tyre thread pattern of the tyre (215).

6. The tyre belt speed sensor (260) according to any previous claim, where the sensor front end (510) comprises a Hall effect sensor (580) arranged to detect passage of a plurality of magnets (585) attached to or embedded in the outer part of the tyre (215), where the sensor back end (520) is configured

to determine the data indicative of the angular speed (ω_b) based on the frequency of detected passages by the Hall effect sensor (580) and on data associated with a tangential distance between the plurality of magnets (585).

7. The tyre belt speed sensor (260) according to any previous claim, where the sensor back end (520) is configured to detect a tyre explosion of the tyre (215) based on a detected disturbance in the sensed motion of the outer surface of the tyre (215).

8. A wheel sensor assembly comprising a tyre belt speed sensor (260) according to any previous claim and a wheel rim speed sensor or wheel axle speed sensor arranged to determine a rotational velocity of a rim or axle of the wheel, respectively.

9. A wheel unit assembly comprising a wheel (101, 102, 103, 200) with a tyre (215) arranged supported on a wheel rim (220), and a tyre belt speed sensor (260) according to any previous claim.

10. A heavy-duty vehicle (100) comprising one or more tyre belt speed sensors (260) according to any previous claim.

11. A computer system (130, 800) for controlling motion of a heavy-duty vehicle (100), the system comprising at least one tyre belt speed sensor (260) according to any of claims 1-7, at least one axle speed sensor (250), and processing circuitry,

where the axle speed sensor (250) is arranged to determine an angular speed (ω_m) of a drive axle associated with a wheel (101, 102, 103, 200) of the heavy-duty vehicle (100) that supports the tyre (215), and to output data indicative of the angular speed (ω_m) of the drive axle on an axle speed sensor output port,

where the processing circuitry is arranged to receive the data indicative of the angular speed (ω_m) of the drive axle and the data indicative of the angular speed (ω_b) of the tyre belt (210), and

where the processing circuitry is arranged to determine a longitudinal tyre force (F_x) associated with the wheel (101, 102, 103, 200) based on the data indicative of the angular speed (ω_m) of the drive axle and based on the data indicative of the angular speed (ω_b) of the tyre belt (210).

12. The computer system (130, 800) according to claim 11,

where the processing circuitry is arranged to obtain data indicative of a wheel slip (λ_x) associated with the tyre (215), and an inverse tyre model (600) representative of a relationship between wheel slip and longitudinal tyre force at different road friction (μ) and tyre normal force (F_x) conditions,

where the processing circuitry is arranged to determine a longitudinal tyre force (F_x) generating capability based on the wheel slip (λ_x), the longitudinal tyre force (F_x), and the inverse tyre model (600).

13. A computer system (130, 800) for controlling motion of a heavy-duty vehicle (100), the system comprising a tyre belt speed sensor (260) according to any of claims 1-7, a vehicle speed sensor, and processing circuitry,

where the vehicle speed sensor is arranged to determine data indicative of a longitudinal speed (v_x) of the vehicle (100) relative to a road surface (104) supporting the vehicle (100),

where the processing circuitry is arranged to determine a wheel slip (λ_x) associated with the tyre (215) based on the data indicative of the vehicle speed (v_x) and on the data indicative of the angular speed (ω_b) of the tyre belt (210).

14. A computer system (130, 800) for determining a longitudinal tyre force (F_x) associated with at least one wheel (101, 102, 103, 200) comprised in a wheel and drive axle system (300) on a heavy-duty vehicle (100), the computer system (130, 800) comprising processing circuitry configured to

obtain data indicative of an angular speed (ω_m) of a drive axle of the wheel (101, 102, 103, 200),

obtain data indicative of an angular speed (ω_b) of a tyre belt (210) of the wheel (101, 102, 103, 200),

determine a pretension torque (x_1) of a mechanical system comprising the drive axle and the at least one wheel, in response to an applied torque (T_m) at the drive axle, and

determine the longitudinal tyre force (F_x) based on the pretension torque (x_1) and on a pre-determined set of mechanical properties of the at least one wheel and drive axle system (300).

15. The computer system (130, 800) according to claim 14, where the set of mechanical properties of the at least one wheel and drive axle system (300) comprises a lumped stiffness coefficient (k) and a lumped damping coefficient (d) of the wheel and drive axle system (300).

16. The computer system (130, 800) according to claim 15, where the pre-determined set of mechanical properties of the at least one wheel and drive axle system (300) comprises a system model given by

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & \frac{1}{i} & -1 \\ -\frac{k}{J_m \cdot i} & -\frac{d}{J_m \cdot i^2} & \frac{d}{J_m \cdot i} \\ \frac{k}{(J_b + m \cdot r^2)} & \frac{d}{(J_b + m \cdot r^2) \cdot i} & \frac{-d}{(J_b + m \cdot r^2)} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{J_m} \\ 0 \end{bmatrix} \cdot T_m$$

where

$$x_1 = \frac{1}{i} \cdot \theta_m - \theta_b$$

$$x_2 = \dot{\theta}_m$$

$$x_3 = \dot{\theta}_b$$

i is a gear ratio of a gear transmission arrangement, $\theta_m - \theta_b$ is a difference in angular position of the drive axle and the tyre belt, J_m and J_b are inertias of a power source of the wheel and drive axle system (300) and the tyre belt respectively, m is a mass of the heavy-duty vehicle (100), r is a radius of the wheel, and T_m is a torque applied at the drive axle in the wheel and drive axle system (300).

17. The computer system (130, 800) according to claim 16, where the processing circuitry is configured to determine the longitudinal tyre force (F_x) as

$$\hat{F}_x = \frac{d\dot{x}_1 + kx_1 - J_b\dot{x}_3}{r}$$

18. The computer system (130, 800) according to any of claims 14-17, where the at least one wheel (101, 102, 103, 200) on the heavy-duty vehicle (100) is arranged to be driven by a combustion engine via the drive axle system, where the processing circuitry is configured to determine a torque T_m applied by the combustion engine based on a torque sensor.

19. The computer system (130, 800) according to any of claims 14-18, where the at least one wheel (101, 102, 103, 200) on the heavy-duty vehicle (100) is arranged to be driven by an electric machine via the drive axle system, where the processing circuitry is configured to determine a torque T_m applied by the electric machine based on a state of a control unit of the electric machine, and/or based on a torque sensor.

20. The computer system (130, 800) according to claim 19, where the processing circuitry is configured to obtain the data indicative of the angular speed (ω_m) of the drive axle of the wheel (101, 102, 103, 200) from the control unit of the electric machine.

21. A vehicle motion management, VMM, system (420) comprising a computer system (130, 800) according to any of claims 14-20.

22. The VMM system (420) according to claim 21, comprising a motion support device, MSD, coordination function (470) arranged to coordinate actuation of one or more MSDs based on the determined longitudinal tyre force (F_x) of the at least one wheel (101, 102, 103, 200) on the heavy-duty vehicle (100).

23. A computer-implemented method, performed by a computer system (130, 800), for sensing a rotational motion of a tyre (215) on a heavy-duty vehicle (100), the method comprising

providing (Sa1) a sensor front end (510) configured to sense (515) motion of an outer surface of the tyre (215), where the outer surface of the tyre (215) is arranged to engage a road surface (104) supporting the heavy-duty vehicle (100) in use,

providing (Sa2) a sensor back end (520) configured to determine data indicative of an angular speed (ω_b) of a tyre belt (210) of the tyre (215) based on the motion sensed by the sensor front end (510), and

determining (Sa3) the rotational motion of the tyre (215) by the sensor back end (520) as the angular speed (ω_b) of the tyre belt (210) of the tyre (215).

24. The computer-implemented method according to claim 23, further comprising

monitoring (Sa4) the rotational motion of the tyre (215) and detecting a tyre explosion based on a disturbance in the monitored rotational motion by the tyre (215).

25. A computer-implemented method, performed by a computer system (130, 800), for controlling motion of a heavy-duty vehicle (100) comprising a wheel (101, 102, 103, 200) that supports a tyre (215), the method comprising

providing (Sb1) at least one tyre belt speed sensor (260) and at least one axle speed sensor (250),

determining (Sb2) an angular speed (ω_m) of a drive axle associated with the wheel (101, 102, 103, 200) by the axle speed sensor (250),

determining (Sb3) and angular speed (ω_b) of a tyre belt (210) associated with the wheel (101, 102, 103, 200) by the tyre belt speed sensor (260), and

determining (Sb4) a longitudinal tyre force (F_x) associated with the wheel (101, 102, 103, 200) based on the angular speed (ω_m) of the drive axle and based on the angular speed (ω_b) of the tyre belt (210).

26. The computer-implemented method according to claim 25, further comprising

obtaining (Sb5) data indicative of a wheel slip (λ_x) associated with the tyre (215), and an inverse tyre model (600) representative of a relationship between wheel slip and longitudinal tyre force at different road friction (μ) and tyre normal force (F_x) conditions, and

determining (Sb6) a longitudinal tyre force (F_x) generating capability of the wheel based on the wheel slip (λ_x), the longitudinal tyre force (F_x), and the inverse tyre model (600).

27. A computer program product comprising program code for performing, when executed by the processing circuitry, the method of any of claims 23-26.

28. A non-transitory computer-readable storage medium comprising instructions, which when executed by processing circuitry, cause the processing circuitry to perform the method of any of claims 23-26.

29. A tyre (215, 501) comprising a plurality of magnets (585) attached to or embedded in an outer part of the tyre (215, 501).

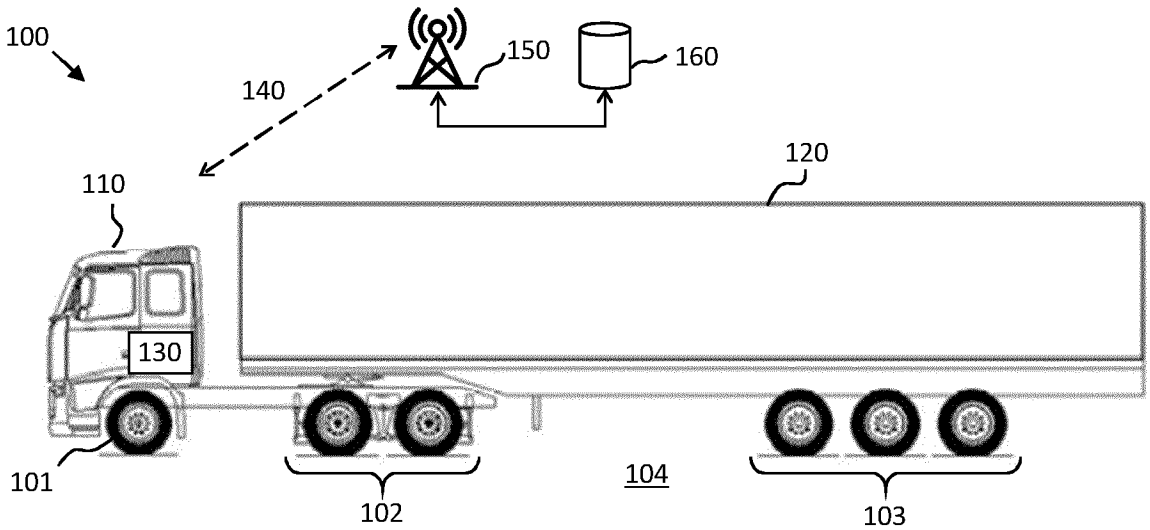

100
140
150
160
120
110
130
101
102
104
103

FIG. 1

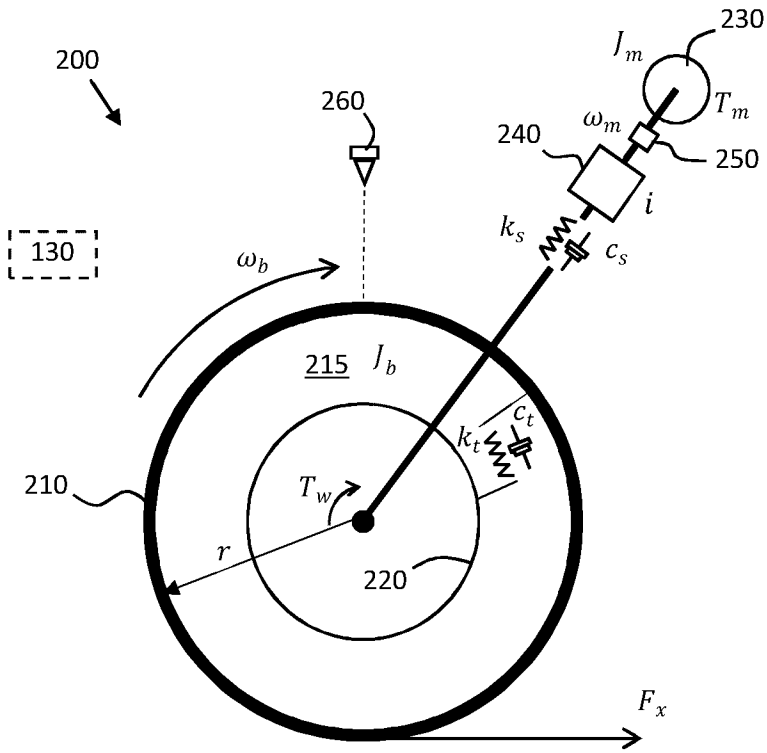

200
260
230
J_m
T_m
ω_m
240
250
i
k_s
c_s
130
ω_b
215
J_b
c_t
k_t
210
T_w
r
220
F_x

FIG. 2

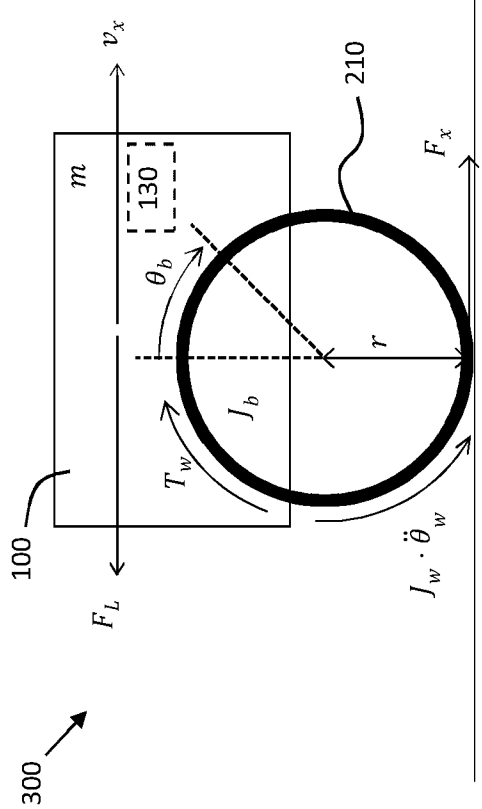

300
100
F_L
v_x
m
130
θ_b
J_b
T_w
210
F_x
r
$J_w \cdot \ddot{\theta}_w$

FIG. 3A

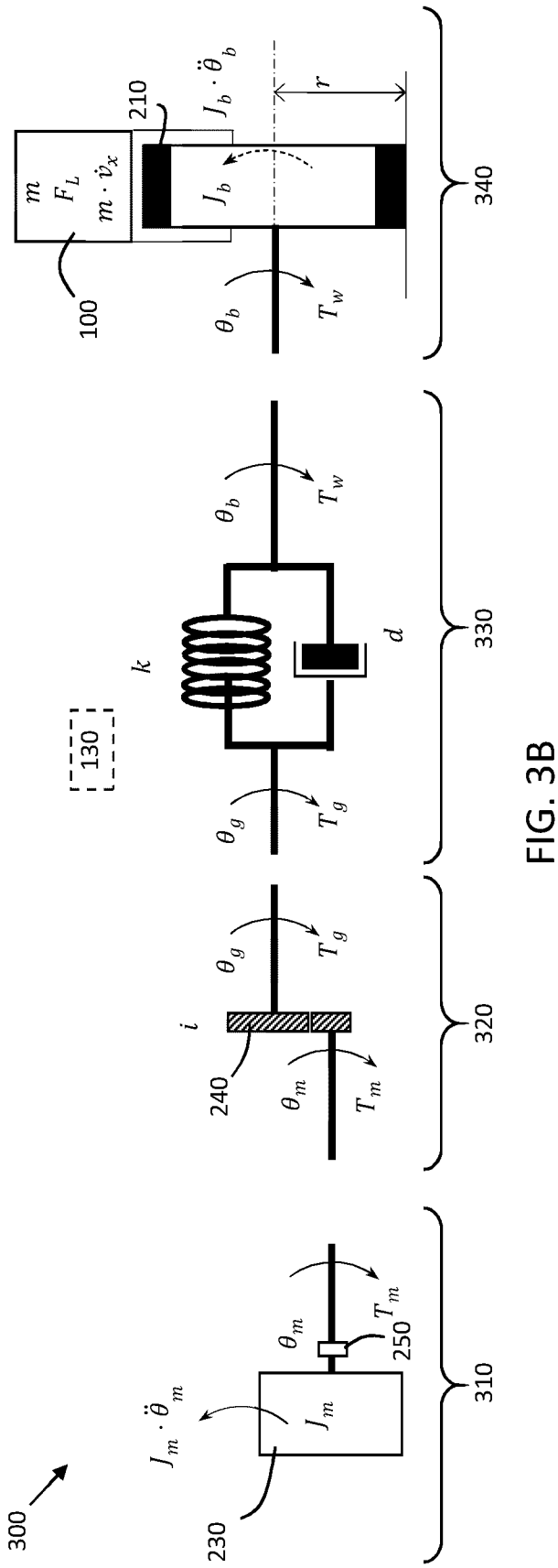

300
230
$J_m \cdot \ddot{\theta}_m$
J_m
θ_m
T_m
250
310
240
i
θ_g
T_g
320
130
k
d
θ_b
T_w
330
100
m
F_L
$m \cdot \dot{v}_x$
210
$J_b \cdot \ddot{\theta}_b$
J_b
r
340

FIG. 3B

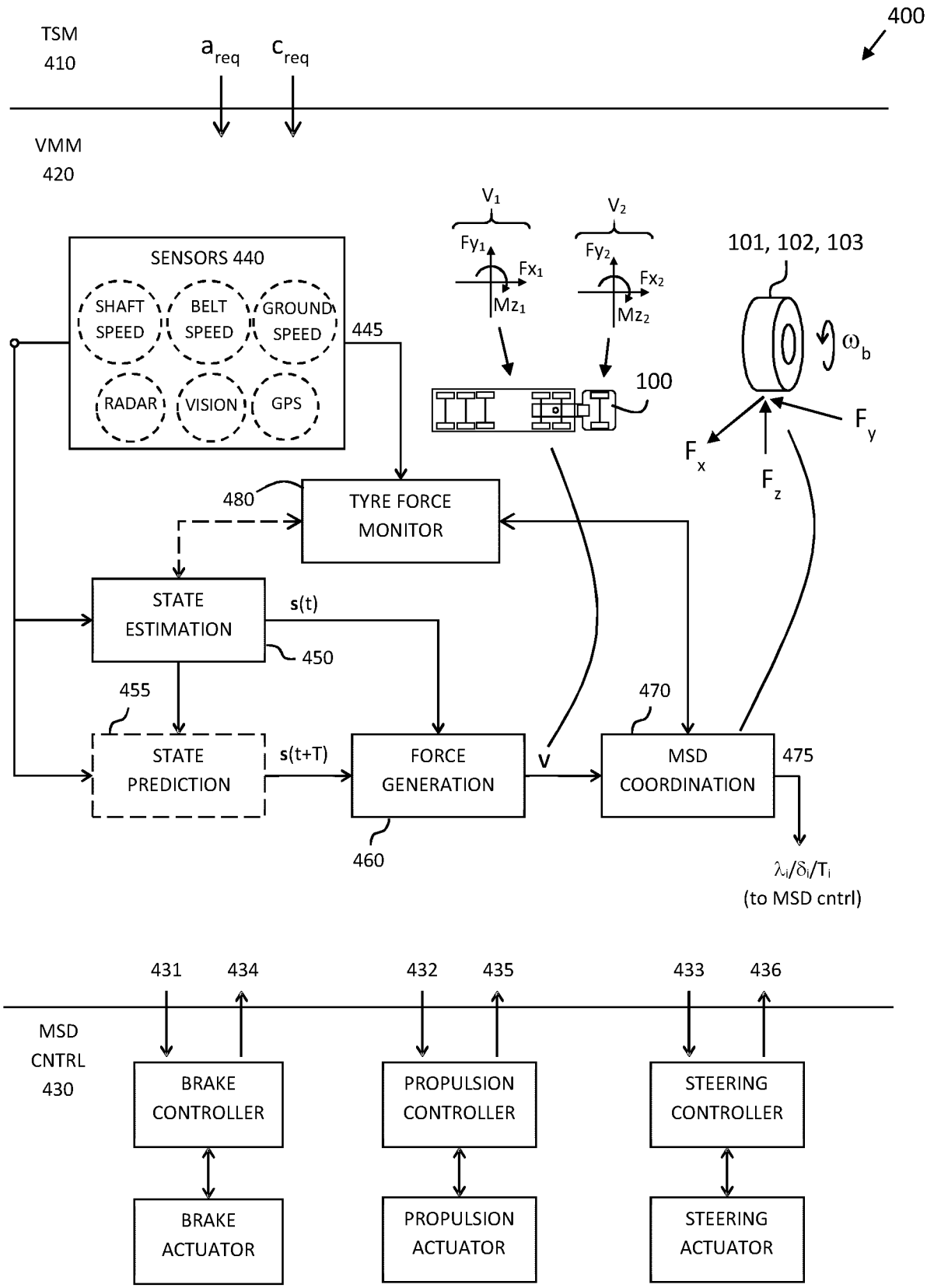

400
TSM
410
a_{req}
c_{req}
VMM
420
SENSORS 440
SHAFT SPEED
BELT SPEED
GROUND SPEED
RADAR
VISION
GPS
445
V_1
V_2
Fy_1
Fx_1
Mz_1
Fy_2
Fx_2
Mz_2
100
101, 102, 103
ω_b
F_y
F_x
F_z
480
TYRE FORCE MONITOR
STATE ESTIMATION
s(t)
450
455
STATE PREDICTION
s(t+T)
FORCE GENERATION
460
v
470
MSD COORDINATION
475
$\lambda_i/\delta_i/T_i$
(to MSD cntrl)
431
434
432
435
433
436
MSD CNTRL
430
BRAKE CONTROLLER
PROPULSION CONTROLLER
STEERING CONTROLLER
BRAKE ACTUATOR
PROPULSION ACTUATOR
STEERING ACTUATOR

FIG. 4

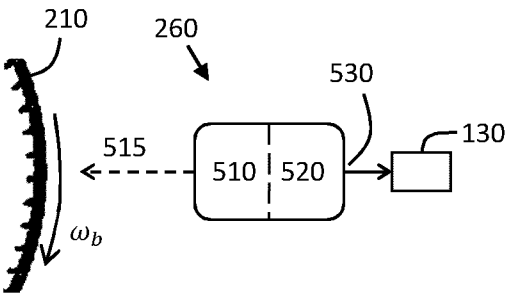


FIG. 5A

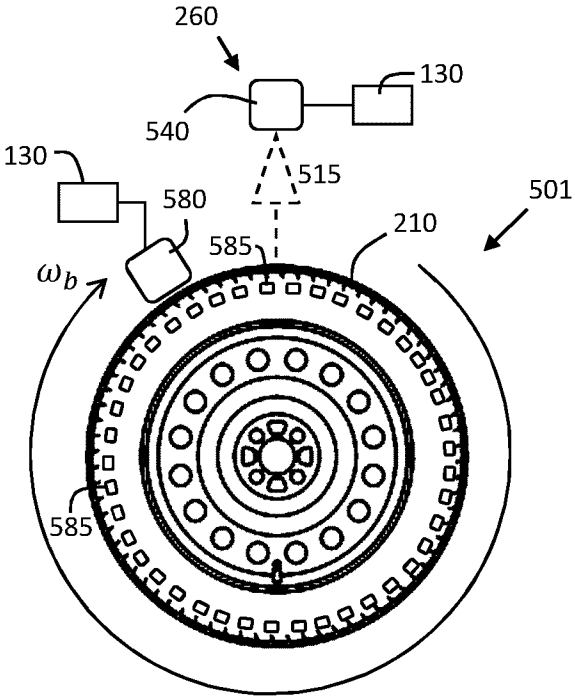


FIG. 5B

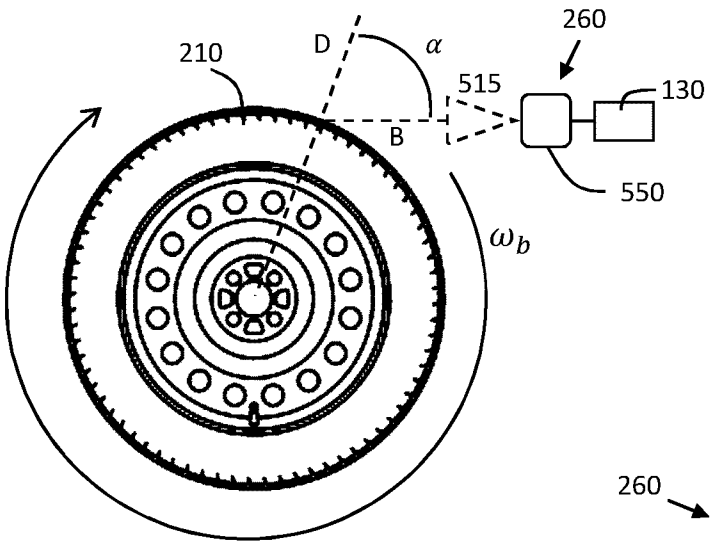


FIG. 5C

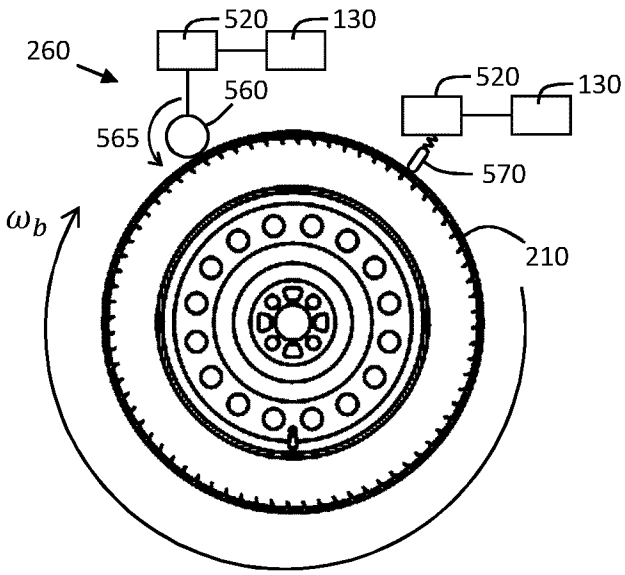


FIG. 5D

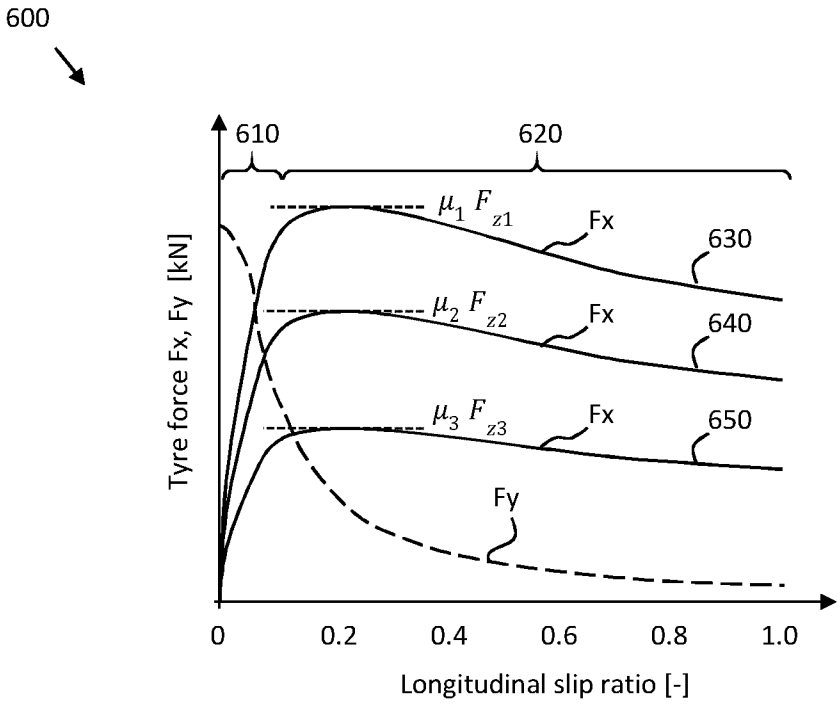

600
610
620
$\mu_1 F_{z1}$
Fx
630
$\mu_2 F_{z2}$
Fx
640
$\mu_3 F_{z3}$
Fx
650
Fy
Tyre force Fx, Fy [kN]
0
0.2
0.4
0.6
0.8
1.0
Longitudinal slip ratio [-]

FIG. 6

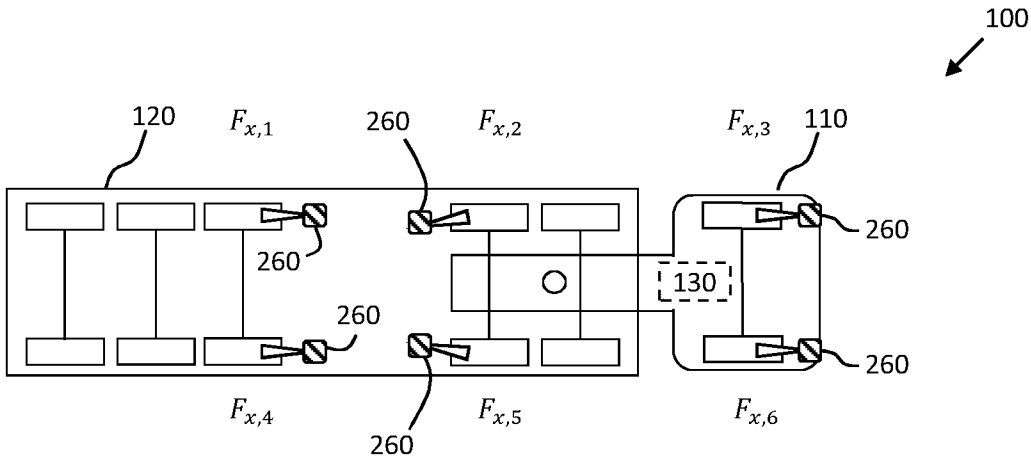

100
120
$F_{x,1}$
260
$F_{x,2}$
$F_{x,3}$
110
260
260
130
260
260
$F_{x,4}$
$F_{x,5}$
$F_{x,6}$
260

FIG. 7

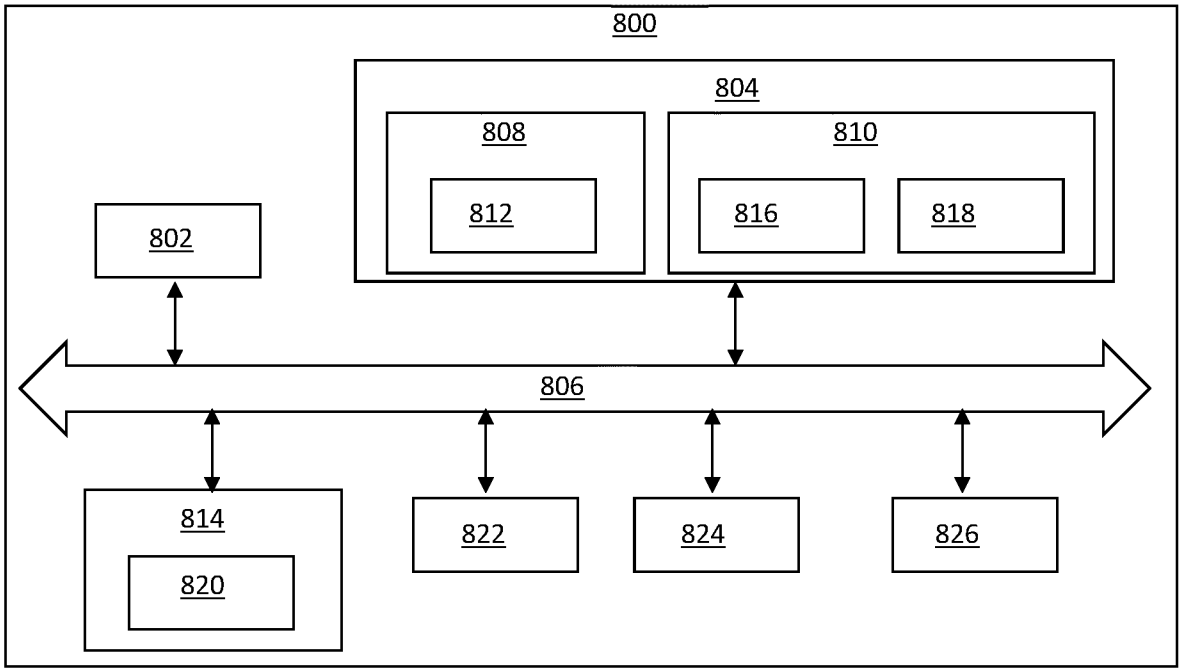


FIG. 8

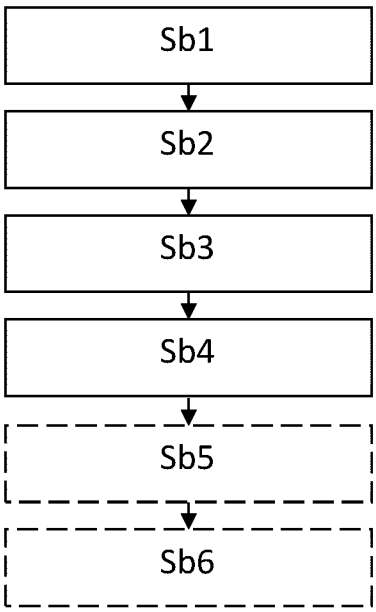


FIG. 9B

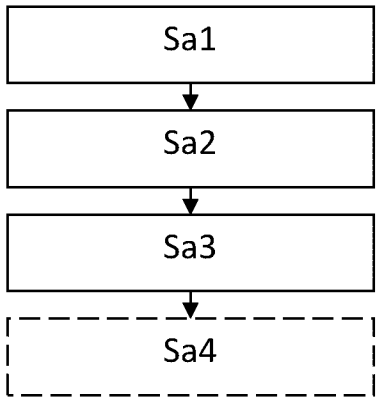


FIG. 9A

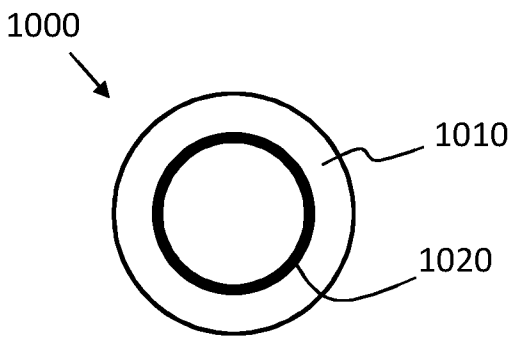


FIG. 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2023/065014

A. CLASSIFICATION OF SUBJECT MATTER
INV. B60W40/12 B60C23/06 G01P1/04 B60T8/172
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
B60W B60C G01P B60T

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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Y	page 9 - page 20; figures 1-4	4,11-13, 21-28
A		14-20

Y	US 2 665 897 A (CLARK MOLLENHOUR DELBERT) 12 January 1954 (1954-01-12) column 2 - column 4; figures 1,2	4

X	DE 10 2017 218902 A1 (VOLKSWAGEN AG [DE]) 25 April 2019 (2019-04-25) paragraphs [0007], [0024] - [0031]; claims 1,7; figures 1-4	1,2,7,10

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[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

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"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
10 November 2023	20/11/2023

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Billen, Karl

2

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INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2023/065014

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	US 2006/219000 A1 (MIYOSHI AKIHIRO [JP] ET AL) 5 October 2006 (2006-10-05) paragraph [0036] - paragraph [0076]; figures 1-6b	1,6,8,9, 29
Y	EP 3 851 346 A1 (VOLVO TRUCK CORP [SE]) 21 July 2021 (2021-07-21) cited in the application	11-13, 21-28
A	the whole document	14-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2023/065014

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