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(54) Title: WHEEL COMPRISING A NON-PNEUMATIC TIRE

(57) **Abstract:** A wheel comprising a non-pneumatic tire for a road vehicle, such as an autonomous vehicle, in which the wheel may avoid sudden failure, improve hydroplaning and/or other wet traction performance, provide more ride comfort, generate less noise, exhibit less rolling resistance, enhance stiffness characteristics for maneuvers, and/or have sensing capabilities. The non-pneumatic tire may comprise: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with a road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road.

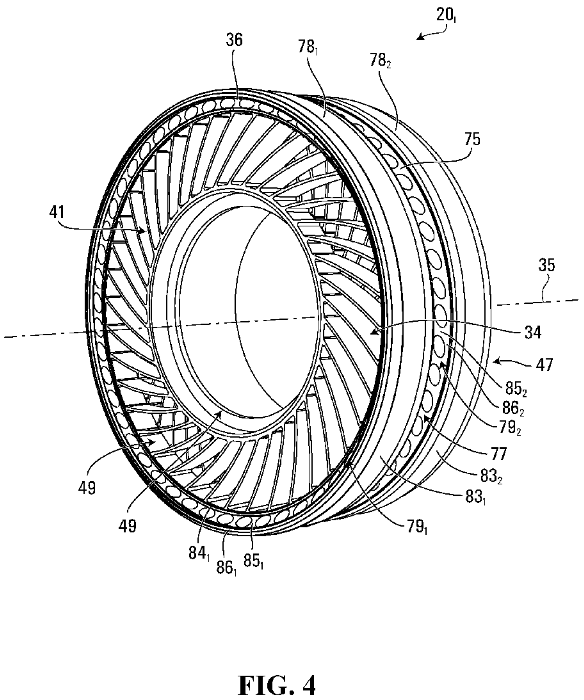

FIG. 4

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WHEEL COMPRISING A NON-PNEUMATIC TIRE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims priority from U.S. Provisional Patent Application 62/677,136 filed on May 28, 2018 and incorporated by reference herein.

FIELD

This disclosure relates to non-pneumatic tires (NPTs) for road vehicles (e.g., automobiles, light trucks, and heavy trucks), including autonomous (a.k.a. “self-driving“ or “driverless”) vehicles.

BACKGROUND

Non-pneumatic tires (NPTs) have advantages over pneumatic tires. For example, NPTs are not pressure vessels, as are pneumatic tires. They cannot fail due to air pressure loss. Additionally, a pneumatic tire’s sidewall and crown are pre-tensioned membranes. As such, a pneumatic tire resembles an acoustic drum that efficiently transmits vibrations. Hence, an NPT may offer advantages in noise and ride comfort, compared to a traditional pneumatic tire, as well as safety.

In spite of these advantages, NPTs are not conventionally used in on-road automotive market products. There are good reasons for this. For instance, performance of modern radial tires has been maturing over the last 70 years – in fact, the radial tire has concurrently evolved with the modern automobile. Pneumatic tire weaknesses are now compensated by other systems, such as tire pressure monitoring systems, which alert a driver if a tire begins to lose air pressure.

Radial tire dominance, however, may be challenged, including by the advent of autonomous vehicles. Notably, autonomous vehicles may have tire performance requirements that are different from current cars and trucks. Some performance aspects may be similar to those of the current cars and trucks, other performance aspects may need to be greatly superior, while other performance aspects may be less stringent.

NPTs have been disclosed that address some performance short-falls of pneumatic tires.

For example, certain NPTs are tension-based in that they support loading by tension in tensile members (e.g., spokes). However, NPTs that are tension-based are faced with performance challenges compared to pneumatic tires, since NPT designs may induce problems such as spoke vibrations that may cause issues with noise and/or comfort (e.g., U.S. Patent 8,646,497) and since there are essentially no commercially-available NPTs for automotive use.

Other non-pneumatic tires are not tension-based, but rather pass load from their ground contact area to their wheel hub primarily through compression and/or bending of part of their structure. These NPTs may be fine for certain intended uses. However, due to physics of operation, it may be difficult or impossible to combine various requirements for an automotive tire.

Therefore, there is a need for a new, better approach for NPT design for automotive applications, including for autonomous road vehicles.

SUMMARY

According to various aspects, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle (e.g., an autonomous vehicle) on a road, in which the wheel may avoid sudden failure, improve hydroplaning and/or other wet traction performance, provide more ride comfort, generate less noise, exhibit less rolling resistance, enhance stiffness characteristics for maneuvers, and/or have sensing capabilities. The non-pneumatic tire may comprise: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road.

For example, according to an aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for an autonomous vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic engages the road. At 80% of a rated load of the non-pneumatic tire: a rolling resistance coefficient of the non-pneumatic tire is no more than (i.e., equal to or less than) 0.012; and a torsional stiffness of the non-pneumatic tire is at least (i.e., equal to or greater than) 11000 N-m / radian.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and a plurality of spokes extending radially inwardly from the annular beam towards an axis of rotation of the non-pneumatic tire and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above the axis of rotation of the non-pneumatic tire are in tension. At 80% of a rated load of the non-pneumatic tire, a fundamental frequency of each of the spokes is no more than 65 Hz, a normalized power of each of the spokes is no more than 2 watts, and a torsional stiffness of the non-pneumatic tire is at least 11000 N-m / radian.

According to another aspect, this disclosure relates to a set of non-pneumatic wheels for a vehicle on a road. Each of the non-pneumatic wheels comprises a non-pneumatic tire comprising: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road. A noise level in a cabin of the vehicle at a given speed of the vehicle is at least 1 dB lower when the vehicle is equipped with the non-pneumatic tire of each of the non-pneumatic wheels than if the vehicle was instead equipped with an equivalent commercially-available pneumatic tire at each of an equivalent set of pneumatic wheels that would replace the non-pneumatic wheels.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground; and a tread disposed radially outwardly of the annular beam. At a given load on the non-pneumatic tire and a given water depth on the road, a hydroplaning speed of the non-pneumatic tire when the tread is at a tread wear indicator of the non-pneumatic tire is at least 85% of the hydroplaning speed of the non-pneumatic tire at a full depth of the tread.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground. At 80% of a rated load of the non-pneumatic tire, a hydroplaning speed of the non-pneumatic tire at 3 mm of tread depth is at least 85% of the hydroplaning speed of the non-pneumatic tire at full tread depth, when water depth is between 3 and 4 mm.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground; and a tread disposed radially outwardly of the annular beam. The non-pneumatic tire comprises an outer circumferential channel that is deeper than a tread depth of the tread.

According to another aspect, there is provided a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground; and a tread disposed radially outwardly of the annular beam. A tread area of the non-pneumatic tire comprises a central channel that runs circumferentially around an outer radial extent of the annular beam and divides the tread area into two halves. A depth of the central channel extends at least 14 mm below a depth of the tread.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground. At 80% of a rated load of the non-pneumatic tire, a gross contact pressure at the contact patch of the non-pneumatic tire is at least 0.25 MPa, and a vertical stiffness of the non-pneumatic tire is no more than 32 kg/mm.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground. A cornering coefficient of the non-pneumatic tire at 80% of a rated load of the non-pneumatic tire is at least 0.16, and the cornering coefficient of the non-pneumatic tire at 160% of the rated load of the non-pneumatic tire is at least 0.12.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the wheel engages the ground. A cornering coefficient of the non-pneumatic tire at 160% of a rated load of the non-pneumatic tire is at least 65% of the cornering coefficient of the non-pneumatic tire at 80% of the rated load of the non-pneumatic tire.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and a plurality of spokes extending radially inwardly from the annular beam to a hub and configured to resiliently deform as the non-pneumatic tire engages the road. A distance between a point of intersection of a given one of the spokes with the annular beam to a point of intersection of the given one of spokes with the hub is at least 115% of a radial distance from an outer radial extent of the hub to an inner radial extent of the annular beam.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; a plurality of spokes extending radially inwardly from the annular beam to a hub and configured to resiliently deform as the non-pneumatic tire engages the road; and a tread disposed radially outwardly of the annular beam. The non-pneumatic tire is characterized by any of or any combination of:

- an outer diameter between 580 mm and 730 mm, and a width between 190 mm and 260 mm;
- a rated load between 400 kg and 900 kg;
- a hydroplaning speed of at least 90 kph when a tread depth is at a wear indicator (e.g., wear bar height) of the tread, for a water depth of between 2 and 4 mm, at 80% of the rated load of the non-pneumatic tire;
- a rolling resistance coefficient of no more than 0.011 at 80 kph, at 80% of the rated load of the non-pneumatic tire;
- a fundamental frequency of each of the spokes of no more than 85 Hz, at 80% of the rated load of the non-pneumatic tire;
- a normalized power of each of the spokes that is no more than 2.3 watts, at 80% of the rated load of the non-pneumatic tire;
- a torsional rigidity of at least 11 kN-m / radian, at 80% of the rated load of the non-pneumatic tire;
- a lateral rigidity that is at least equal to a vertical rigidity, at 80% of the rated load of the non-pneumatic tire; and
- a cornering coefficient at 160% of the rated load of the non-pneumatic tire that is at least 65% of the cornering coefficient at 80% of the rated load of the non-pneumatic tire.

According to another aspect, this disclosure relates to a wheel comprising a non-pneumatic tire for a vehicle on a road. The non-pneumatic tire comprises: an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road such that, when the non-pneumatic tire is loaded, an upper portion of the annular support above an axis of rotation of the non-pneumatic tire is in tension. The non-pneumatic tire comprises a sensor.

These and other aspects of this disclosure will now become apparent to those of ordinary skill in the art upon review of a description of embodiments in conjunction with accompanying drawings.

BRIEF DESCRIPTION OF DRAWINGS

A detailed description of embodiments is provided below, by way of example only, with reference to accompanying drawings, in which:

Figures 1 to 3 show an example of a vehicle comprising a wheel including a non-pneumatic tire to engage a road in accordance with an embodiment;

Figure 4 shows an isometric view of the wheel comprising the non-pneumatic tire;

Figures 5 to 7 show a side view, a top view and a front view of the wheel comprising the non-pneumatic tire;

Figure 8 shows a close-up view of a peripheral area of the non-pneumatic tire;

Figure 9 shows a cut plane view of part of the non-pneumatic tire;

Figure 10 shows a side view of the non-pneumatic tire when loaded against the road;

Figure 11 shows tangent delta and dynamic extension modulus vs. temperature of an elastomer of the non-pneumatic tire;

Figure 12 shows a crack propagation rate vs. strain energy release rate of an elastomer of the non-pneumatic tire;

Figure 13 shows results of a finite element model of the non-pneumatic tire, including a contact patch of the non-pneumatic tire with the road;

Figure 14 shows hydroplaning speed vs. ground contact pressure for two tires having different footprint aspect ratios;

Figure 15 shows a cross-section in a radial–circumferential (R-θ) plane of a tension-based non-pneumatic tire in accordance with another embodiment;

Figure 16 shows an example of relationship between a maximum number of full-width spokes and a maximum spoke angle for a tension-based non-pneumatic tire;

Figure 17 shows an example of spoke length vs. spoke angle for a tension-based non-pneumatic tire;

Figure 18 shows an example of torsional stiffness vs. spoke angle of a tension-based non-pneumatic tire;

Figure 19 shows an example of spoke frequency and spoke power vs. number of spokes for a tension-based non-pneumatic tire;

Figure 20 shows an example of spoke frequency and spoke power vs. spoke length for a tension-based non-pneumatic tire;

Figure 21 shows an example of rolling resistance vs. contact pressure for a non-pneumatic tire;

Figure 22 shows an example of cornering stiffness vs. load for a non-pneumatic tire and a similarly-sized pneumatic tire; and

Figures 23 to 27 show another embodiment in which the non-pneumatic tire comprises one or more sensors.

It is to be expressly understood that the description and drawings are only for purposes of illustrating certain embodiments and are an aid for understanding. They are not intended to and should not be limiting.

DETAILED DESCRIPTION OF EMBODIMENTS

Figure 1 shows an example of an embodiment of a road vehicle 10 comprising wheels 20_1-20_4 on a road 11. The road vehicle 10 is designed to legally carry people or cargo on the road 11, which is part of a public road infrastructure (e.g., public streets, highways, etc.). In this embodiment, the road vehicle 10 is an automobile (e.g., a passenger car). More particularly, in this embodiment, the road vehicle 10 is an autonomous vehicle (sometimes referred to as a “self-driving” or “driverless” vehicle) that is operable without human control, including by steering, accelerating, and decelerating (e.g., braking) itself autonomously without human control, to travel to a destination. Although it can drive itself, in some embodiments, the autonomous vehicle 10 may be controlled by a human driver in some situations.

As further discussed later, in this embodiment, the wheels 20_1-20_4 are non-pneumatic (i.e., airless) and may be designed to enhance their use and performance, including, for example, to avoid sudden failure, improve hydroplaning and/or other wet traction performance, provide more ride comfort, generate less noise, exhibit less rolling resistance, enhance stiffness characteristics for maneuvers, and/or have sensing capabilities, which may be useful for the autonomous vehicle 10.

In this embodiment, the autonomous vehicle 10 comprises a frame 12, a powertrain 14, a steering system 16, a suspension 18, the wheels 20_1-20_4, a cabin 22, and a control system 15 that is configured to operate the vehicle 10 autonomously (i.e,, without human control). The autonomous vehicle 10 has a longitudinal direction, a widthwise direction, and a heightwise direction.

The powertrain 14 is configured to generate power for the autonomous vehicle 10, including motive power for the wheels 20_1-20_4 to propel the vehicle 10 on the road 11. To that end, the powertrain 14 comprises a power source (e.g., a primer mover) that includes one or more motors. For example, in some embodiments, the power source may comprise an internal combustion engine, an electric motor (e.g., powered by a battery), or a combination of different types of motor (e.g., an internal combustion engine and an electric motor). The powertrain 14 can transmit power from the power source 13 to one or more of the wheels 20_1-20_4 in any suitable way (e.g., via a transmission, a differential, a shaft engaging (i.e., directly connecting) a motor and a given one of the wheels 20_1-20_4, etc.).

The steering system 16 is configured to steer the autonomous vehicle 10 on the road 11. In this embodiment, the steering system 16 is configured to turn front ones of the wheels 20_1-20_4 to change their orientation relative to the frame 12 of the vehicle 10 in order to cause the vehicle 10 to move in a desired direction.

The suspension 18 is connected between the frame 12 and the wheels 20_1-20_4 to allow relative motion between the frame 12 and the wheels 20_1-20_4 as the autonomous vehicle 10 travels on the road 11. For example, the suspension 18 may enhance handling of the vehicle 10 on the road 11 by absorbing shocks and helping to maintain traction between the wheels 20_1-20_4 and the road 11. The suspension 18 may comprise an arrangement of springs and dampers. A spring may be a coil spring, a leaf spring, a gas spring (e.g., an air spring), or any other elastic object used to store mechanical energy. A damper (also sometimes referred to as a “shock absorber”) may be a fluidic damper (e.g., a pneumatic damper, a hydraulic damper, etc.), a magnetic damper, or any other object which absorbs or dissipates kinetic energy to decrease oscillations. In some cases, a single device may itself constitute both a spring and a damper (e.g., a hydropneumatic device).

The cabin 22 is configured to be occupied by one or more occupants of the autonomous vehicle 10. In this embodiment, with additional reference to Figure 2, the cabin 22 comprises windows 21_1-21_W, seats 23_1-23_S, and a user interface 70 that is configured to interact with one or more occupants of the vehicle 10. The user interface 70 comprises an input portion including one or more input devices (e.g., a set of buttons, levers, dials, etc., a touchscreen, a microphone, etc.) allowing an occupant of the vehicle 10 to input commands and/or other information into the vehicle 10 and an output portion including one or more output devices (e.g., a display, a speaker, etc.) to provide information to an occupant of the vehicle 10. The output portion of the user interface 70 which may comprise an instrument panel (e.g., a dashboard) which provides indicators (e.g., a speedometer indicator, a tachometer indicator, etc.) related to operation of the vehicle 10.

The control system 15 is configured to operate the autonomous vehicle 10, including to steer, accelerate, and decelerate (e.g., brake) the autonomous vehicle 10, autonomously (i.e,, without human control) as the autonomous vehicle 10 progresses to a destination along a route on the road 11. To that end, with further reference to Figure 3, the control system 15 comprises a controller 80 and a sensing apparatus 82 to perform actions controlling the vehicle 10 (e.g., actions to steer, accelerate, decelerate, etc.) to move it towards its destination on the road 11 based on a computerized perception of an environment of the vehicle 10.

While its control system 15 enables it to drive itself, the autonomous vehicle 10 may be controlled by a human driver, such as an occupant in the cabin 22, in some situations. For example, in some embodiments, the control system 15 may allow the autonomous vehicle 10 to be selectively operable either autonomously (i.e., without human control) or under human control (i.e., by a human driver) in various situations (e.g., the autonomous vehicle 10 may be operable in either of an autonomous operational mode and a human-controlled operational mode). For instance, in this embodiment, the user interface 70 of the cabin 22 may comprise an accelerator 30 (e.g., an acceleration pedal), a braking device 28 (e.g., a brake pedal), and a steering device 17 (e.g., a steering wheel) that can be operated by a human driver in the cabin 22 to control the vehicle 10 on the road 11.

The controller 80 is a processing apparatus configured to process information received from the sensing apparatus 82 and possibly other sources in order to perform actions controlling the autonomous vehicle 10, including to steer, accelerate, and decelerate the vehicle 10, towards its destination on the road 11. In this embodiment, the controller 80 comprises an interface 166, a processing portion 168, and a memory portion 170, which are implemented by suitable hardware and software.

The interface 166 comprises one or more inputs and outputs allowing the controller 80 to receive input signals from and send output signals to other components to which the controller 80 is connected (i.e., directly or indirectly connected), including the sensing apparatus 82, the powertrain 14, and the steering system 16, and possibly other components such as the user interface 70, a communication interface 68 configured to communicate over a communication network (e.g., a cellular or other wireless network, for internet and/or other communications) and/or with one or more other vehicles that are near the autonomous vehicle 10 (i.e., for inter-vehicle communications), etc.

The processing portion 168 comprises one or more processors for performing processing operations that implement functionality of the controller 80. A processor of the processing portion 168 may be a general-purpose processor executing program code stored in the memory portion 170. Alternatively, a processor of the processing portion 168 may be a specific-purpose processor comprising one or more preprogrammed hardware or firmware elements (e.g., application-specific integrated circuits (ASICs), electrically erasable programmable read-only memories (EEPROMs), etc.) or other related elements.

The memory portion 170 comprises one or more memories for storing program code executed by the processing portion 168 and/or data (e.g., maps, vehicle parameters, etc.) used during operation of the processing portion 168. A memory of the memory portion 170 may be a semiconductor medium (including, e.g., a solid-state memory), a magnetic storage medium, an optical storage medium, and/or any other suitable type of memory. A memory of the memory portion 170 may be read-only memory (ROM) and/or random-access memory (RAM), for example.

In some embodiments, the controller 80 may comprise and/or interact with one or more other control units of the autonomous vehicle 10. For example, in some embodiments, the controller 80 may comprise and/or interact with a powertrain control unit of the powertrain 14, such as an engine control unit (ECU), a transmission control unit (TCU), etc.

The sensing apparatus 82 comprises a set of sensors 90_1-90_S to sense aspects of the environment of the vehicle 10 and generate sensor information indicative of these aspects of the environment of the vehicle 10 that is provided to the controller 80 in order to control the vehicle 10 towards its destination on the road 11. The sensor information can be used by the controller 80 to determine actions which are to be performed by the autonomous vehicle 10 in order for the vehicle 10 to continue to its destination. The sensors 90_1-90_S can provide situational information proximate to the vehicle 10, including any potential hazards proximate to the vehicle 10.

The sensors 90_1-90_S may include any suitable sensing device. For instance, in some embodiments, the sensors 90_1-90_S may comprise a camera (e.g., video, stereoscopic, etc.) and/or other imaging device, a Light Detection and Ranging (LIDAR) device, a radar device, a wheel speed sensor, a GPS and/or other location sensor, and/or any other suitable sensing device.

The autonomous vehicle 10 may be implemented in any suitable way. For example, in some embodiments, the autonomous vehicle 10, including its control system 15, may be implemented as a Waymo^{TM} vehicle as described at https://waymo.com/safetyreport/, a or a vehicle described in U.S. Patent 8,818,608, all of which are incorporated by reference herein.

The wheels 20_1-20_4 engage the road 11 for traction of the vehicle 10. Each wheel 20_i comprises a non-pneumatic tire 34 for contacting the road 11 and a hub 32 for connecting the wheel 20_i to an axle 17. The non-pneumatic tire 34 is a compliant wheel structure that is not supported by gas (e.g., air) pressure and that is resiliently deformable (i.e., changeable in configuration) as the wheel 20_i contacts the ground.

In this embodiment, the wheel 20_i may avoid sudden failure, improve hydroplaning and/or other wet traction performance, provide more ride comfort, generate less noise, exhibit less rolling resistance, and/or enhance stiffness characteristics for maneuvers, which may be useful for the autonomous vehicle 10.

For example, in some embodiments, the non-pneumatic tire 34 may be designed specifically for and dedicated to use on autonomous vehicles such as the autonomous vehicle 10. For instance, in some embodiments, the non-pneumatic tire 34 may be homologated for use on autonomous vehicles such as the autonomous vehicle 10 (e.g., by a homologating entity such as a manufacturer of the autonomous vehicle 10 and/or a company managing performance of the autonomous vehicle 10 to comply with governmental requirements to be homologated or certified).

With additional reference to Figures 4 to 10, the wheel 20_i has an axis of rotation 35, which defines an axial direction (also referred to as a “Y” direction) parallel to the axis of rotation 35 of the wheel 20_i, a vertical direction (also referred to as a “Z” direction) that is normal to the axis of rotation 35 of the wheel 20_i, and a horizontal direction (also referred to as a “X” direction) that is normal to the axis of rotation 35 of the wheel 20_i and the vertical direction and can be viewed as corresponding to a heading direction of the wheel 20_i. The axial direction of the wheel 20_i can also be referred to as a lateral or widthwise direction of the wheel 20_i, while each of the vertical direction and the horizontal direction of the wheel 20_i can also be referred to as radial direction of the wheel 20_i. The wheel 20_i also has a circumferential direction (also referred to as a “C” direction). The wheel 20_i has an outer diameter D_W and a width W_W. It comprises an inboard lateral side 47 for facing towards a center of the vehicle 10 in the widthwise direction of the vehicle 10 and an outboard lateral side 49 opposite its inboard lateral side 47.

Similarly, the non-pneumatic tire 34 has an axial direction, a vertical direction, a horizontal direction, and a circumferential direction, which respectively correspond to the axial direction, the vertical direction, the horizontal direction, and the circumferential direction of the wheel 20_i, has an inner diameter D_{TI}, an outer diameter D_T, and a width W_T, and comprises an inboard lateral side 53 and an outboard lateral side 57, which are respectively part of the inboard lateral side 47 and the outboard lateral side 49 of the wheel 20_i.

When it is in contact with the ground, the non-pneumatic tire 34 has an area of contact 25 with the road 11, which may be referred to as a “contact patch” of the non-pneumatic tire 34 with the road 11. The contact patch 25 of the non-pneumatic tire 34 has a dimension L_C, referred to as a “length”, in the horizontal direction of the wheel 20_i and a dimension W_C, referred to as a “width”, in the lateral direction of the wheel 20_i.

In this embodiment, a size range for the non-pneumatic tire 34 may be such that its width W_T is between 180 mm and 245 mm and its outer diameter D_T is between 580 mm and 705 mm. A rated load of the non-pneumatic tire 24, which refers to a load for which the non-pneumatic tire 34 is designed to operate properly such that it can properly support that load, may be between 400 kg and 900 kg. It can be viewed as a maximum load for continuous operation at legal speed. For example, in various embodiments, the rated load of the non-pneumatic tire 24 may be indicated on the non-pneumatic tire 24 itself and/or conveyed as information regarding the non-pneumatic tire 24 by an entity, such as a manufacturer of the non-pneumatic tire 24 and/or the vehicle 10 (e.g., in a user manual, technical specifications, etc.). A speed capability of the non-pneumatic tire 34, which refers to a maximum speed at which the non-pneumatic tire 34 can be used at its rated load at steady-state, may be about 140 kph (i.e., kilometer per hour). The speed capability of the non-pneumatic tire 34 may be higher in other examples (e.g., up to 200 kph).

Compared to a conventional automobile always driven by a human driver, in some embodiments, the autonomous vehicle 10 may benefit from:

a) Systems that are fail operable;
b) Higher levels of traction in poor weather, especially in hydroplaning, as water depth on the road 11 is very difficult to sense before contact;
c) Much improved comfort, to allow making the cabin 22 more similar to a train car. For instance, in some cases a reduction of cabin noise of around 10+ dB may be useful, compared to an expensive luxury car sold today;
d) Low energy consumption; and/or
e) Efficient algorithms for computer control of all driving functions.

In some embodiments, these criteria for the autonomous vehicle 10 may create tire performance criteria as follows:

a) Sudden failure is unacceptable. Thus, a failure due to rapid air loss is unacceptable. Either a non-pneumatic tire, a so-called “run-flat” tire, or some method by which an inflated tire cannot rapidly lose air is mandated;
b) Higher hydroplaning and wet traction performance, which should not deteriorate with tire wear;
c) Much better comfort and lower noise generation, compared to a standard radial tire. One first order design direction is to reduce vertical stiffness;
d) Less rolling resistance (e.g., a rolling resistance coefficient of 0.01 or lower), reduced frontal area (e.g., a narrow tire is preferred over a wide tire); and/or
e) Sufficiently high lateral stiffness and cornering stiffness, so that transient vehicle maneuvers are well behaved. Sufficient torsional stiffness can be required for efficient operation with ABS systems (e.g., see Interaction of ABS with Tire Torsional Dynamics, September 13, 2011, CUICAR Presentation).

Taken together, respective ones of these criteria are quite challenging and may be incompatible for a radial tire, since, for example, one may have to:

- Reduce vertical stiffness, while maintaining high lateral stiffness and cornering stiffness, while maintaining or reducing tire width;
- Decouple hydroplaning performance from tread wear;
- Maintain or reduce rolling resistance while adding a run-flat performance; and/or
- Greatly reduce vibration transmission without increasing rolling resistance.

The wheel 20_i, including its non-pneumatic tire 34, may allow these criteria to be met for the autonomous vehicle 10 in some embodiments, as further discussed later.

The non-pneumatic tire 34 may be implemented in various ways. In this embodiment, the non-pneumatic tire 34 comprises an annular beam 36 and an annular support 41 that is disposed between the annular beam 36 and the hub 32 of the wheel 20_i and configured to support loading on the non-pneumatic tire 34 as the non-pneumatic tire 34 engages the ground. In this embodiment, the non-pneumatic tire 34 is tension-based such that the annular support 41 is configured to support the loading on the non-pneumatic tire 34 by tension. That is, under the loading on the non-pneumatic tire 34, the annular support 41 is resiliently deformable such that a lower portion 27 of the annular support 41 between the axis of rotation 35 of the non-pneumatic tire 34 and the contact patch 25 of the non-pneumatic tire 34 is compressed (e.g., with little reaction force vertically) and an upper portion 29 of the annular support 41 above the axis of rotation 35 of the non-pneumatic tire 34 is in tension to support the loading.

The annular beam 36 of the non-pneumatic tire 34 is configured to deflect under the loading on the non-pneumatic tire 34 at the contact patch 25 of the non-pneumatic tire 34 with the ground. For instance, the annular beam 36 functions like a beam in transverse deflection. An outer peripheral extent 46 of the annular beam 36 and an inner peripheral extent 48 of the annular beam 36 deflect at the contact patch 25 of the non-pneumatic tire 34 under the loading on the non-pneumatic tire 34. In this embodiment, the annular beam 36 is configured to deflect such that it applies a homogeneous contact pressure along the length L_C of the contact patch 25 of the non-pneumatic tire 34 with the ground. The annular beam 36 has a radius R_{BEAM} defined by its outer peripheral extent 36.

More particularly, in this embodiment, the annular beam 36 comprises a shear beam 39 configured to deflect predominantly by shearing at the contact patch 25 under the loading on the non-pneumatic tire 34. That is, under the loading on the non-pneumatic tire 34, the shear beam 39 deflects significantly more by shearing than by bending at the contact patch 25. The shear beam 39 is thus configured such that, at a center of the contact patch 25 of the non-pneumatic tire 34 in the circumferential direction of the non-pneumatic tire 34, a shear deflection of the shear beam 39 is significantly greater than a bending deflection of the shear beam 39. For example, in some embodiments, at the center of the contact patch 25 of the non-pneumatic tire 34 in the circumferential direction of the non-pneumatic tire 34, a ratio of the shear deflection of the shear beam 39 over the bending deflection of the shear beam 39 may be at least 1.2, in some cases at least 1.5, in some cases at least 2, in some cases at least 3, and in some cases even more (e.g., 4 or more). For instance, in some embodiments, the annular beam 36 may be designed based on principles discussed in U.S. Patent 9,751,270, which is hereby incorporated by reference herein, in order to achieve the homogeneous contact pressure along the length L_C of the contact patch 25 of the non-pneumatic tire 34 with the ground.

In this example of implementation, the shear beam 39 comprises an outer annular portion 31, an inner annular portion 33, and a shearing annular portion 38 between the outer annular portion 31 and the inner annular portion 33 that are configured to cause the shear beam 39 to deflect more by shearing than by bending at the contact patch 25 of the tire 34. In this embodiment, the shearing annular portion 38 comprises a plurality of voids 56_1-56_N between the outer annular portion 31 and the inner annular portion 33, which may be respectively referred to as an “outer band” 31 and an “inner band” 33 of the shear beam 39. The shear beam 39 also comprises a plurality of interconnecting members 37_1-37_P that extend between the outer band 31 and the inner band 33 and are disposed between respective ones of the voids 56_1-56_N. The interconnecting members 37_1-37_P may be referred to as “webs” such that the shear beam 39 may be viewed as comprising “web-like” or “webbing” portions.

Each of the inner band 31 and the outer band 33 extends continuously in the circumferential direction of the non-pneumatic tire 34. A thickness t_{BAND} of each of the inner band 33 and the outer band 33 in the radial direction of the tire 34 may have any suitable value. In various embodiments, the thickness t_{BAND} of the inner band 33 and/or the thickness t_{BAND} of the outer band 33 may be identical or different.

The voids 56_1-56_N of the shear beam 39 help the shear beam 39 to deflect predominantly by shearing at the contact patch 25 under the loading on the non-pneumatic tire 34. In this embodiment, the voids 56_1-56_N are openings that extend from the inboard lateral side 54 to the outboard lateral side 49 of the non-pneumatic tire 34.

That is, the openings 56_1-56_N extend laterally though the shear beam 39 in the axial direction of the non-pneumatic tire 34. The openings 56_1-56_N may extend laterally without reaching the inboard lateral side 54 and/or the outboard lateral side 49 of the non-pneumatic tire 34 in other embodiments. In this example, a cross-section of each of the openings 56_1-56_N is oblong. The cross-section of each of the openings 56_1-56_N may be shaped differently in other examples (e.g., polygonal, partly curved and partly straight, etc.). In some cases, different ones of the openings 56_1-56_N may have different shapes. In some cases, the cross-section of each of the openings 56_1-56_N may vary in the axial direction of the wheel 20_i. For instance, in some embodiments, the openings 56_1-56_N may be tapered in the axial direction of the wheel 20_i such that their cross-section decreases inwardly axially (e.g., to help minimize debris accumulation within the openings 56_1-56_N).

The shear beam 39, including the voids 56_1-56_N and the interconnecting members 37_1-37_P may be arranged in any other suitable way in other embodiments. For example, in other embodiments, the shear beam 39 may comprise one or more intermediate bands between the inner band 33 and the outer band 33, the voids 56_1-56_N and/or the interconnecting members 37_1-37_P may have any other suitable shapes, etc.

In this embodiment, the non-pneumatic tire 34 comprises a tread 50 for enhancing traction between the non-pneumatic tire 34 and the ground. The tread 50 is disposed about the outer peripheral extent 46 of the annular beam 36, in this case about the outer band 31 of the shear beam 39. The tread 50 may comprise a plurality of tread recesses and a plurality of tread projections such that each of the tread recesses is disposed between adjacent ones of the tread projections. The tread 50 may be implemented in any suitable way in other embodiments (e.g., may have a smooth outer surface without tread recesses or projections).

The annular support 41 is configured to support the loading on the non-pneumatic tire 34 as the non-pneumatic tire 34 engages the ground. As mentioned above, in this embodiment, the annular support 41 is configured to support the loading on the non-pneumatic tire 34 by tension. More particularly, in this embodiment, the annular support 41 comprises a plurality of support members 42_1-42_T that are distributed around the non-pneumatic tire 34 and resiliently deformable such that, under the loading on the non-pneumatic tire 34, lower ones of the support members 42_1-42_T in the lower portion 27 of the annular support 41 (between the axis of rotation 35 of the non-pneumatic tire 34 and the contact patch 25 of the non-pneumatic tire 34) are compressed and bend while upper ones of the support members 42_1-42_T in the upper portion 29 of the annular support 41 (above the axis of rotation 35 of the non-pneumatic tire 34) are tensioned to support the loading. As they support load by tension when in the upper portion 29 of the annular support 41, the support members 42_1-42_T may be referred to as “tensile” members.

In this embodiment, the support members 42_1-42_T are elongated and extend from the annular beam 36 towards the hub 32 generally in the radial direction of the non-pneumatic tire 34. In that sense, the support members 42_1-42_T may be referred to as “spokes” and the annular support 41 may be referred to as a “spoked” support.

More particularly, in this embodiment, the inner peripheral extent 48 of the annular beam 36 is an inner peripheral surface of the annular beam 36 and each spoke 42_i extends from the inner peripheral surface 48 of the annular beam 36 towards the hub 32 generally in the radial direction of the non-pneumatic tire 34 and from a first lateral end 55 to a second lateral end 58 in the axial direction of the non-pneumatic tire 34. In this case, the spoke 42_i extends in the axial direction of the non-pneumatic tire 34 for at least a majority of the width W_T of the non-pneumatic tire 34. For instance, in some embodiments, the spoke 42_i may extend in the axial direction of the non-pneumatic tire 34 for more than half, in some cases at least 60%, in some cases at least 80%, and in some cases an entirety of the width W_T of the non-pneumatic tire 34. Moreover, the spoke 42_i has a thickness T_S measured between opposite surfaces 59, 61 of the spoke 42_i that is significantly less than a length and width of the spoke 42_i.

When the non-pneumatic tire 34 is in contact with the ground and bears a load (e.g., part of a weight of the construction vehicle 10), respective ones of the spokes 42_1-42_T that are disposed in the upper portion 29 of the spoked support 41 (i.e., above the axis of rotation 35 of the non-pneumatic tire 34) are placed in tension while respective ones of the spokes 42_1-42_T that are disposed in the lower portion 27 of the spoked support 41 (i.e., adjacent the contact patch 25) are placed in compression. The spokes 42_1-42_T in the lower portion 27 of the spoked support 41 which are in compression bend in response to the load. Conversely, the spokes 42_1-42_T in the upper portion 29 of the spoked support 41 which are placed in tension support the load by tension.

A sectional height H_T of the non-pneumatic tire 34 is half of a difference between the outer diameter D_T and the inner diameter D_{TI} of the tire 34. The sectional height H_T of the tire may be significant in relation to the width W_T of the tire 34. In other words, an aspect ratio AR of the tire 34 corresponding to the sectional height H_T over the width W_T of the tire 34 may be relatively high. For instance, in some embodiments, the aspect ratio AR of the tire 34 may be at least 70%, in some cases at least 90%, in some cases at least 110%, and in some cases even more. Also, the inner diameter D_{TI} of the tire 34 may be significantly less than the outer diameter D_T of the tire 34 as this may help for compliance of the non-pneumatic tire 34. For example, in some embodiments, the inner diameter D_{TI} of the non-pneumatic tire 34 may be no more than half of the outer diameter D_T of the non-pneumatic tire 34, in some cases less than half of the outer diameter D_T of the non-pneumatic tire 34, in some cases no more than 40% of the outer diameter D_T of the non-pneumatic tire 34, and in some cases even a smaller fraction of the outer diameter D_T of the non-pneumatic tire 34. In this specific example of implementation, the non-pneumatic tire 34 may be a 215/65R15 tire so that D_T = 41”, W_T = 215 mm and D_{TI} = 15”.

In this embodiment, the non-pneumatic tire 34 comprises an outer circumferential channel 77 that extends in the circumferential direction of the non-pneumatic tire 34.

The outer circumferential channel 77 is a recess between lateral parts 78_1, 78_2 of the non-pneumatic tire 34. This may be useful, for example, to evacuate or otherwise manage water on the road 11 for hydroplaning and wet traction, as further discussed later.

The lateral parts 78_1, 78_2 of the non-pneumatic tire 34, which can also be referred to as inboard and outboard parts of the non-pneumatic tire 34, respectively comprise lateral (i.e., inboard and outboard) parts 79_1, 79_2 of the annular beam 36 and lateral parts 83_1, 83_2 of the tread 50. More particularly, in this embodiment, the lateral parts 79_1, 79_2 of the annular beam 36 respectively comprise lateral parts 84_1, 84_2 of the inner band 31, lateral parts 85_1, 85_2 of the shearing annular portion 38, and lateral parts 86_1, 86_2 of the outer band 33. In this embodiment, the lateral parts 85_1, 85_2 of the shearing annular portion 38 include respective ones of the voids 56_1-56_N extending therethrough.

In this embodiment, the outer circumferential channel 77 is disposed substantially centrally in the axial direction of the non-pneumatic tire 34 so that it bisects the non-pneumatic tire 34 at the annular beam 36 and the tread 50. In other embodiments, the outer circumferential channel 77 may be located elsewhere in the non-pneumatic tire 34. Also, in other embodiments, the non-pneumatic tire 34 may comprise two or more outer circumferential channels such as the outer circumferential channel 77. In this example, the outer circumferential channel 77 extends continuously around the tire 34. In other example, the outer circumferential channel 77 may not extend completely around the tire 34 (e.g., may include segments that are spaced from one another around the tire 34).

A radial depth d_c of the outer circumferential channel 77 (i.e., a depth of the outer circumferential channel 77 in the radial direction of the non-pneumatic tire 34) may be greater than a tread depth d_t of the tread 50 (i.e., a depth of a tread recess disposed between adjacent tread projections of the tread 50). For example, in this embodiment, the tread depth d_t is 8 mm and the radial depth d_c of the outer circumferential channel

77 is 22 mm, while a width w_c of the outer circumferential channel 77 is 25 mm. Thus, if the tread 50 is completely worn away, the radial depth d_c of the outer circumferential channel 77 will be 14 mm.

In this embodiment, a radially outer portion of the annular beam 36 is divided into two halves by the outer circumferential channel 77. Also, in this case, the voids 56_1-56_N of the annular beam 36 extend transversally to the axial direction of the non-pneumatic tire 34. More particularly, in this case, the voids 56_1-56_N are angled in a directional fashion. This may enable higher efficiency for water evacuation from the outer circumferential channel 77 when the tire 34 is rolling at high speed through standing water.

Figure 9 provides a cut view of the non-pneumatic tire 34, passing through a radial – axial plane. In this embodiment, the spoked support 41 comprises a plurality of (in this case three) spoked portions 220, 230, 240 that are different, distributed in the axial direction of the non-pneumatic tire 34, and include respective ones of the spokes 42_1-42_T. In this example, respective ones of the spokes 42_1-42_T of the spoked portions 220, 240 have identical cross-sections in the R-T plane and are oriented in a same way, while respective ones of the spokes 42_1-42_T of the spoked section 230 have the same cross-section but are oriented differently than (e.g., generally oppositely to) the spokes 42_1-42_T of the spoked portions 220, 240 (e.g., in a mirror image). The spoked portions 220, 230, 240 are not connected along the radial length of their spokes 42_1-42_T. Thus, each of the spoked portions 220, 230, 240 operates independently.

The hub 32 is disposed centrally of the non-pneumatic tire 34 and connects the wheel 20_i to the axle 17. The hub 32 may be implemented in any suitable manner.

The wheel 20_i may be made up of one or more materials. The non-pneumatic tire 34 comprises a tire material 45 that makes up at least a substantial part (i.e., a substantial part or an entirety) of the non-pneumatic tire 34. The hub 32 comprises a hub material 72 that makes up at least a substantial part of the hub 32. In some embodiments, the tire material 45 and the hub material 72 may be different materials. In other embodiments, the tire material 45 and the hub material 72 may be a common material (i.e., the same material).

In this embodiment, the tire material 45 constitutes at least part of the annular beam 36 and at least part of the spokes 42_1-42_T. Also, in this embodiment, the tire material 45 constitutes at least part of the tread 50. More particularly, in this embodiment, the tire material 45 constitutes at least a majority (e.g., a majority or an entirety) of the annular beam 36, the tread 50, and the spokes 42_1-42_T. In this example of implementation, the tire material 45 makes up an entirety of the non-pneumatic tire 34, including the annular beam 36, the spokes 42_1-42_T, and the tread 50. The non-pneumatic tire 34 is thus monolithically made of the tire material 45. In this example, therefore, the annular beam 36 is free of (i.e., without) substantially inextensible reinforcement running in the circumferential direction of the wheel 20_i (e.g., a layer of metal, composite (e.g., carbon fibers, other fibers), and/or another material that is substantially inextensible running in the circumferential direction of the non-pneumatic tire 34). In that sense, the annular beam 36 may be said to be “unreinforced”.

The tire material 45 is elastomeric. For example, in this embodiment, the tire material 45 comprises a polyurethane (PU) elastomer. Various considerations for selection of the tire material 45 are further discussed below.

The non-pneumatic tire 34 may comprise one or more additional materials in addition to the tire material 45 in other embodiments (e.g., different parts of the annular beam 36, different parts of the tread 50, and/or different parts of the spokes 42_1-42_T may be made of different materials). For example, in some embodiments, different parts of the annular beam 36, different parts of the tread 50, and/or different parts of the spokes 42_1-42_T may be made of different elastomers. As another example, in some embodiments, the annular beam 36 may comprise one or more substantially inextensible reinforcing layers running in the circumferential direction of the wheel 20_i (e.g., one or more layers of metal, composite (e.g., carbon fibers, other fibers), and/or another material that is substantially inextensible running in the circumferential direction of the wheel 20_i).

In this embodiment, the hub material 72 is polymeric. More particularly, in this example of implementation, the hub material 72 is elastomeric. For example, in this embodiment, the hub material 72 comprises a polyurethane (PU) elastomer. The hub material 72 may be any other suitable material in other embodiments. For example, in other embodiments, the hub material 72 may comprise a stiffer polyurethane material. In some embodiments, the hub material 72 may not be polymeric. For instance, in some embodiments, the hub material 72 may be metallic (e.g., steel, aluminum, etc.).

The hub 32 may comprise one or more additional materials in addition to the hub material 72 in other embodiments (e.g., different parts of the hub 32 may be made of different materials).

Figure 11 shows characteristics of an example of a thermoplastic elastomer that may be used to make the non-pneumatic tire 34 in some embodiments. Tangent delta is a measure of hysteresis. Here, the tangent delta is 0.12 at 10ºC, decreasing to 0.06 at 60ºC. At a normal operating temperature of about 40ºC, the value is 0.07. This is quite low. The elastomer is of high modulus also. At 40ºC, the dynamic extension modulus is 170 MPA.

Figure 12 shows a crack propagation performance of the elastomer. Crack propagation rate is shown relative to strain energy release rate. For normal operation of the non-pneumatic tire 34, the maximum strain energy release in key portions of the structure is about 2 N-mm / mm^2. At this level, the crack propagation rate is 1.1e-8 mm / cycle. For a tire of 2 meter circumference, this provides a service life of more than 150,000 km.

The non-pneumatic tire 34 of Figures 4 to 10 has been modeled extensively with finite element analysis (e.g., using the program Abaqus). Additionally, it has been reduced to practice via advanced 3D printing, with a 0.4:1 scale model. Many aspects of these design elements have been reduced to practice with a 245/70R12 NPT, which has been rigorously tested, and used in validating finite element modeling procedures.

The wheel 20_i may be manufactured in any suitable way. For example, in some embodiments, the tire 34 and/or the hub 32 may be manufactured via centrifugal casting, a.k.a. spin casting, which involves pouring one or more materials of the wheel 20_i into a mold that rotates about an axis. The material(s) is(are) distributed within the mold via a centrifugal force generated by the mold's rotation. In some cases, vertical spin casting, in which the mold's axis of rotation is generally horizontal, may be used. In other cases, horizontal spin casting, in which the mold's axis of rotation is generally vertical, may be used. As another example, in some embodiments, the tire 34 and/or the hub 32 may be manufactured via injection molding by injecting material into a mold. The wheel 20_i may be manufactured using any other suitable manufacturing processes in other embodiments.

A structure of the spoked support 41 may be complex in some embodiments. For example, in some embodiments, the spoked portions 220, 230, 240 may be independently molded separately from one another, then assembled together in the non-pneumatic tire 34 by using techniques such as sonic welding. Furthermore, it is possible to design thermoplastic tooling that is capable of demolding similar structures. Pop-out slides and cams may be employed that interactively separate one spoked portion from another while in the forming process, and then are retracted, thereby enabling demolding.

Stiffness characteristics of the wheel 20_i, including its non-pneumatic tire 34, may be considered.

For example, a radial stiffness K_z of the wheel 20_i refers to a rigidity of the wheel 20_i in the radial direction of the wheel 20_i (e.g., the vertical direction of the wheel 20_i), i.e., a resistance of the wheel 20_i to deformation in the radial direction of the wheel 20_i when loaded in the radial direction of the wheel 20_i. A lateral stiffness K_y of the wheel 20_i refers to a rigidity of the wheel 20_i in the widthwise (i.e., axial) direction of the wheel 20_i, i.e., a resistance of the wheel 20_i to deformation in the widthwise direction of the wheel 20_i when loaded in the widthwise direction of the wheel 20_i. A torsional stiffness K_{tx} of the wheel 20_i about the horizontal direction of the wheel 20_i refers to a torsional rigidity of the wheel 20_i about an axis of torsion parallel to the horizontal direction of the wheel 20_i, i.e., a resistance of the wheel 20_i to torsion about the axis of torsion when subjected to a torque about the axis of torsion resulting from loading in the lateral direction of the wheel 20_i.

The wheel 20_i, including its non-pneumatic tire 34, may be designed to have various features which enhance its performance and that of the autonomous vehicle 10. These features can provide multiple tire functions that may be present simultaneously and may not currently be provided, either by traditional pneumatic tires or by currently-available non-pneumatic tires. Examples of such features will now be discussed.

1. Enhanced hydroplaning and/or wet traction performance

Autonomous cars rely on sensors, such as optical, thermal, or acoustic ones, to identify road conditions. It is very difficult to sense a depth of standing water on a road some distance in front of a traveling vehicle. Yet, hydroplaning speed is strongly related to water depth. In traditional pneumatic tires, tread void greatly improves hydroplaning, as the water can “fill up” the tread void. However, this void decreases as the tire wears. Hydroplaning speed therefore decreases with tread wear. At low tread depth, hydroplaning speed may be quite low.

Autonomous cars may therefore benefit from tires that have high hydroplaning speed performance, which is relatively insensitive to tread depth.

In this embodiment, the non-pneumatic tire 34 comprises a water management structure 75 to manage (e.g., contain and/or direct) water on the road 11, such as to enhance a hydroplaning speed of the autonomous vehicle 10 and/or other wet traction performance characteristics of the tire 34. More particularly, in this embodiment, the water management structure 75 comprises the voids 56_1-56_N extending through the annular beam 36 adjacent to the tread 50 and the outer circumferential channel 77 in the annular beam 36 and the tread 50.

The non-pneumatic tire 34 may have degrees of design freedom that a pneumatic tire does not have. For example, a pneumatic tire must have a pressurized, air-filled cavity, generally constrained by reinforcement that follows an equilibrium curve. During on-road operation in standing water, the water must be evacuated either around a contact patch created by this air-filled cavity, or absorbed into tread grooves. At high speed, hydroplaning may result. In contrast, the non-pneumatic tire 34 includes the water management structure 75 that comprises the voids 56_1-56_N and the outer circumferential channel 77 in the annular beam 36 and the tread 50 through which the water can pass. Also, the outer circumferential channel 77 may be very deep so that its radial depth d_c is greater than the tread depth d_t of the tread 50. Thus, hydroplaning performance may be desensitized from tread wear.

Figure 13 shows an example of FEA of the non-pneumatic tire 34, loaded to 480 kg, in this embodiment. The contact patch 25 is cut in two halves 69_1, 69_2, thanks to the outer circumferential channel 7. The radial depth d_c of the outer circumferential channel 77, even when the tread depth d_t of the tread 50 approaches zero, is more than 14 mm. The width of the outer circumferential channel 77 is 25 mm. As such, the halves 69_1, 69_2 of the contact patch 25 of the tire 34 become independent, as far as water evacuation is concerned.

A tire's footprint aspect ratio (FAR) is the tire's footprint width divided by the tire's footprint length. As the footprint becomes wider, it becomes more difficult to evacuate water around the tire as it rolls at high speed through standing water. The outer circumferential channel 77 of the non-pneumatic tire 34 enables the tire 34 to essentially act like two tires that have a FAR that is half the value the tire would have without the outer circumferential channel 77.

Hydroplaning speed can be approximated as:

$$v_p = 25(p_t)^{0.21}\left(\frac{1.4}{FAR}\right)^{0.5} \qquad \text{Equation 1}$$

Where: v_p is hydroplaning speed in kph
P_t is gross contact patch pressure in KPa
FAR is footprint aspect ratio

Results of Equation (1) are provided in Figure 14 for the case of a FAR of 0.5 and FAR of 1.0, both plotted as functions of pressure. The hydroplaning speed with a FAR of 0.5 is equivalent to the contact patch 25 of the non-pneumatic tire 34 of Figure 13. Essentially, the presence of the outer circumferential channel 77 may increase hydroplaning performance by about 20 kph,

Furthermore, this performance may be minimally affected by tread depth, as the outer circumferential channel 77 remains even when tread depth is near zero. This is a virtue of the capability of the non-pneumatic tire 34 in this embodiment. The annular beam 36 is structural, not pneumatic. Therefore it can be easily divided into two sections, with the deep outer circumferential channel 77 in the middle of the structure.

One limitation of a pneumatic tire is that contact patch gross pressure and vertical stiffness are both tied to inflation pressure. For the non-pneumatic tire 34, this is not the case. For example, in some embodiments, the spoke structure and band may be engineered such that the contact pressure is about 0.27 MPa (40 psi). However, the vertical stiffness is about 27 kg / mm. This is less than a similarly sized pneumatic tire at an inflation pressure of 0.27 MPa.

By engineering the non-pneumatic tire 34 in this fashion, hydroplaning performance may be excellent, while ride comfort is not sacrificed. Vertical stiffness is the first order predictor of ride comfort, and keeping a relatively low value of vertical stiffness will improve comfort.

For example, in some embodiments, at a given load on the non-pneumatic tire 34 and a given water depth on the road 11, the hydroplaning speed of the non-pneumatic tire 34 when the tread 50 is at a tread wear indicator (e.g., tread bar height) of the non-pneumatic tire 34 is at least 85%, in some cases at least 90%, and in some cases at least 95% of the hydroplaning speed of the non-pneumatic tire 34 at full tread depth (e.g., when the non-pneumatic tire 34 is new). For instance, in some embodiments, the tread wear indicator may be reached at 2/32" (approximately 1.6mm) of remaining tread depth. As an example, in some embodiments, at 80% of the rated load of the non-pneumatic tire 34, the hydroplaning speed of the non-pneumatic tire 34 at 3 mm of tread depth is at least 85%, in some cases at least 90%, and in some cases at least 95% of the hydroplaning speed of the non-pneumatic tire 34 at full tread depth, when water depth is between 3 and 4 mm.

2. Reduced noise generation

Tension-based NPTs may be difficult to design for low noise and adequate torsional stiffness. However, these may be required for certain on-road applications. A certain level of torsional stiffness, such as at least about 1.2 N-m / radian, may be required for optimum operation with anti-lock braking systems in some embodiments, as discussed in Interaction of ABS with Tire Torsional Dynamics, September 13, 2011, CUICAR Presentation. Also, as will be explained below, longer spokes with a high number of spokes may be useful for low noise operation.

In this embodiment, the non-pneumatic tire 34 may be designed to generate less noise while being sufficiently stiff in torsion, such as by arranging the spokes 42_1-42_T to be greater in number and/or length and/or by restricting a fundamental frequency and/or a normalized power of each of the spokes 42_1-42_T while making the torsional stiffness of the non-pneumatic tire 34 sufficiently high.

Figure 15 shows a cross-section of another embodiment of the non-pneumatic tire 34 in the R-T plane. The spokes 42_1-42_T connect the hub 32 to the annular beam 36. Each spoke has a length L_S. Each spoke has an inclination angle θ from the radial axis at the spoke/hub interface. The angle alternates from $+\theta$ to $-\theta$, from one spoke to an adjacent spoke, thereby creating a tire that is torsionally neutral when loaded. Another way of saying this is that there is no coupling between a vertical force applied in a contact area and a resultant longitudinal force in the X direction.

For a tension-based NPT, it may be highly useful to have a tire that is neutral in the torsional sense. This can be achieved as shown in Figure 15, or as shown in Figure 9, in which the section 230 is twice as wide as the sections 220 and 240. In this example, the sections 220 and 240 are identical, and each individual spoke has the same spoke angle. The section 230 is the mirror image of the sections 220 and 240. Thus, the non-pneumatic tire 34 is torsionally neutral. Torsional neutrality could also be achieved by having two spoke sections of the same width, with sections that are the mirror image: that is to say that the spoke angle of the first section is equal and opposite to the spoke angle of the second section.

With further reference to Figure 15, the distance L is the distance between an inner radius $R_{I\ BAND}$ of the annular beam 36 and an outer radius $R_{O\ HUB}$ of the hub 32. When the angle θ becomes sufficiently large, the spoke ends approach one another, as shown. Thus, for a case where each spoke traverses the full width of the tire, there is a limit to spoke angle θ, depending on the number of spokes, $R_{O\ HUB}$, and $R_{I\ BAND}$.

Assuming spokes that completely traverse the axial width of the tire 34, the maximum number of spokes as function of spoke angle for a 215/65R15 may be as shown in Figure 16. For 44 spokes, for example, the spoke angle may be 8 degrees, or less. If spokes are perfectly radial, a practical maximum number of spokes is 130. At that point, spoke ends are so close that they become very difficult to form.

The NPT 34 of Figure 4, by contrast, is able to utilize a larger spoke angle with a larger number of spokes. For instance, in some embodiments, 40, 50, or even 60 or more spokes could be used in each spoke section for a spoke angle of 10, 20, 30 degrees or even higher.

For a given distance L (as defined with relation to Figure 15) as the spoke angle θ increases, the spoke length L_S increases. This may be as shown for the 215/65R15 dimension in Figure 17. For radial spokes, the spoke angle is 0 degrees, and the length is 105 mm, which is equal to L. At 30 degree spoke angle, this increases to about 138 mm. As previously disclosed, for angles larger than about 8 degrees, a plurality of spoke sections may be useful.

For spoke durability, it may be highly advantageous to have long spokes that traverse the distance from the hub 32 to the annular beam 36 as a free span. As the spokes 42_1-42_T bend when passing through the contact path 25 of the NPT 34, surface strains result. Spoke surface strain decreases as spoke length increases. Spoke durability may vary with the strain raised to a power of 4, or perhaps higher. Thus, a 10% increase in spoke length may make approximately an improvement of 50% in spoke durability.

Torsional rigidity around the axial direction (Y axis) may be extremely important for on-road applications. Pneumatic tires at nominal inflation pressure have fairly high torsional stiffness – higher than 2.0e4 N-m/radian. However, this is not necessarily the case for a tension-based NPT. For example, as shown in Figure 18, torsional rigidity $K\theta$

is quite low (less than 1.0e4 N-m/radian) for the case of 44 spokes, at a load of 480 kg, when the spoke angle is 0 deg. Kθ increases to 1.6e4 N-m/radian for a spoke angle of 8 degrees, and increases to 5.4e4 N-m/radian for a spoke angle of 30 degrees. For efficient operation with ABS, Kθ may be at least 0.9e4 N-m/radian. Since Kθ decreases somewhat with vertical load, a practical minimum value at a normal operating load (such as Fz = 480 kg) may be Kθ equal to at least 1.6e4 N-m/radian. For some applications, Kθ may be higher than this, and for these cases, a plurality of spoke sections can be used.

To summarize, in some embodiments, it may be highly desirable to have both long spokes (for durability) and a large spoke angle (for high torsional rigidity). While this may be accomplished for some applications using full-width spokes, it may be most efficiently accomplished by using a plurality of spoke sections that are separated in the axial direction.

For a tension-based NPT having full width spokes that form a free span between the hub 32 and the annular beam 36, the spokes 42_1-42_T opposite the contact patch 25 will develop a tension force. Thus, as the tire 34 rolls, one individual spoke will go into tension as it passes through the upper portion of the tire 34, and then go into zero tension and in fact be bent in compression as is passes through the contact patch 25. This is a source of vibration, as each spoke essentially acts like a string. This is the inherent problem that U.S. Patent 8,646,497 attempts to alleviate. However, a more direct method is possible, simply by appealing to basic string vibration characteristics.

For full width spokes, a tension force is approximated in Equation 2:

$$T_S = \pi \frac{F_Z}{N_S} \qquad \text{Equation 2}$$

Where F_Z = tire load

N_S = number of spokes

A fundamental frequency of the spoke is approximated in Equation 3:

$$F_S = \frac{v}{2L_S} = \frac{1}{2L_S}\sqrt{\frac{T_S}{\mu}} \qquad \text{Equation 3}$$

Where v = wave velocity

L_S = spoke length

μ = linear spoke density

F_S = frequency in Hertz

A normalized spoke power can be estimated from Equation 4:

$$P_S = \frac{1}{2}\mu\omega^2 A^2 \pi v \qquad \text{Equation 4}$$

Where ω = frequency in rad/sec

A = spoke displacement amplitude = 1 mm.

To relatively compare the effect of variables, we set A = 1 mm, thereby normalizing the P_S calculation.

An example of spoke frequency and normalized power are shown plotted with respect to spoke number in Figure 19 for the 215/65R15 tire 34 at Fz = 480 kg, spoke length = 108 mm. At this length, 40 full-width spokes may be used with a spoke angle = 10 degrees. For a spoke number greater than 40, more than one spoke section may be used.

For ease of comprehension, where there are multiple spoke sections such as the sections 220, 230 and 240 of Figure 9, spoke number can be taken to be the number of spokes in one spoke section. For spoke frequency, dividing the width of the spoke by two will decrease linear mass density by two, and also decrease the tension by two. Thus, from Equation 3, there is no change. Similarly, there is no change in the total normalized power of two or more spoke sections and one full width spoke section.

Spoke frequency, and especially spoke power, rapidly decrease as the number of spokes increases. For 70 spokes, frequency has decreased to 77 HZ, compared to 97 HZ with only 40 spokes. Spoke power with 70 spokes is only 43% the power with 40 spokes.

Figure 20 shows spoke frequency and power relative to spoke length, with number of spokes = 44. Both vibration frequency and power strongly decrease with spoke length.

These two effects – spoke length and spoke number – may be combined to create a tire that has exceptionally low spoke vibration frequency and power. For example, with a spoke length = 0.15 meters and a spoke number = 64, spoke frequency = 55 HZ and normalized power = 0.86 Watts. This represents a very large reduction compared to a length of 0.108 meters with 40 spokes, which is 98 HZ and 3.4 Watts, respectively.

An automotive application generally requires a specific design space. Disk brakes may require a specific hub inner diameter. Other packaging needs may define a maximum tire outer diameter and width. Thus, a tire dimension like 215/65R15 may be imposed. Given such dimensional constraints, multiple spoke sections provide a design solution to enable larger spoke angles in concert with a high spoke number.

For quiet operation, in some embodiments, the spoke fundamental frequency may be no more than 85 Hz, in some cases no more than 75 Hz, in some cases no more than 65 Hz, and in some cases even less, and/or The normalized spoke power may be no more than 2.3 watts, in some cases no more than 1.75 watts, in some cases no more than 1.4 watts, and in some cases even less.

Meanwhile, in some embodiments, the torsional stiffness of the non-pneumatic tire 34 may be at least 11000 N-m / radian, in some cases at least 13000 N-m / radian, in some cases at least 15000 N-m / radian, and in some cases even more.

A noise level in the cabin 22 of the autonomous vehicle 10 , which can be referred to as a "cabin noise level", may thus be substantially reduced using the non-pneumatic tire 34. For example, in some embodiments, the cabin noise level at a given speed of the vehicle 10 (e.g., 100 kph) may be at least 1 dB lower, in some cases at least 2 dB lower, in some cases at least 3 dB, in some cases at least 4 dB, and in some cases at least 5 dB lower when the vehicle 10 is equipped with the non-pneumatic tire 34 of each of the non-pneumatic wheels 20_1-20_4 than if the vehicle 10 was instead equipped with an equivalent commercially-available pneumatic tire 34*, i.e., which has an outer diameter and a width respectively corresponding to the outer diameter D_W and the width W_W of the non-pneumatic tire 34, at each of an equivalent set of pneumatic wheels that would replace the non-pneumatic wheels 20_1-20_4. This may be measured by initially measuring the cabin noise level at the given speed of the vehicle 10 with the non-pneumatic tire 34 of each of the non-pneumatic wheels 20_1-20_4, removing the non-pneumatic wheels 20_1-20_4 with their non-pneumatic tire 34, mounting the equivalent pneumatic wheels with their equivalent commercially-available pneumatic tire 34* in place of the non-pneumatic wheels 20_1-20_4 with their non-pneumatic tire 34, and measuring the cabin noise level again. For example, at a highway speed of 100 kph, modern luxury cars may achieve an interior cabin noise level of around 60 decibels (dB) using conventional inflated radial tires. Using non-pneumatic tire technologies disclosed herein, a noise reduction of 2 to 5 dB may be achieved.

3. Low rolling resistance

Another need that may exist for an automotive NPT is low rolling resistance. Current radial pneumatic tires have an average rolling resistance force of 11 kg / ton. That is to say, a frictional force in a tire's X-direction at a contact patch of a rolling tire is equal to 0.011 times a vertical load on the tire. This is usually expressed as "kg / ton." For an NPT to compete with the radial tire in an automotive market of autonomous vehicles that may most probably be electric, the NPT's rolling resistance may be at this level or lower.

In this embodiment, the non-pneumatic tire 34 may be designed to minimize a rolling resistance coefficient of the non-pneumatic tire 34 while maintaining suitable stiffness characteristics, such as being sufficiently stiff torsionally and/or vertically.

For example, in some embodiments, at 80% of the rated load of the non-pneumatic tire 34, the rolling resistance coefficient of the non-pneumatic tire 34 may be no more than 0.012, in some cases no more than 0.010, and in some cases even less.

Meanwhile, in some embodiments, the torsional stiffness of the non-pneumatic tire 34 may be at least 11000 N-m / radian, in some cases at least 13000 N-m / radian, in some cases 15000 N-m / radian, and in some cases even more.

Figure 21 shows an example of predicted rolling resistance vs. gross contact pressure for some embodiments of the non-pneumatic tire 34 of Figure 4, when implemented as a 215/65R15 NPT. Ground contact pressure may be changed most easily by increasing the structural stiffness of the annular beam 36, and/or by increasing the modulus of the annular band elastomer. Vertical stiffness, however, may be unchanged, as the spoke design can compensate for the stiffer annular beam.

Rolling resistance decreases as contact pressure increases. At a gross contact pressure of 0.27 (40 psi), rolling resistance is less than 9 kg / ton. This is very competitive, even for a pneumatic tire.

Rolling resistance, including the rolling resistance coefficient of the non-pneumatic tire 34, may be measured using SAE J1269. Gross footprint contact area and vertical stiffness of the non-pneumatic tire 34 may be calculated using SAE J2704.

The tread 50 may be designed to reduce the rolling resistance of the tire 34. For instance, the material of the tread 50 may have lower hysteresis energy loss, i.e., lower tan δ is, to lower the rolling resistance. As an example, in some embodiments, the material of the tread 50 may be a polyurethane elastomer, which may be thermoplastic or thermoset.

4. Enhanced cornering or other maneuvering capability

Both pneumatic and non-pneumatic tires develop cornering forces as a slip angle is applied while rolling. A cornering stiffness may be defined as a cornering force developed at 1 degree slip angle. Cornering stiffness may be calculated from SAE J1987.

Cornering stiffness increases as vertical load increases. This may be as shown in Figure 23 for the 215/65R15 size for a reference pneumatic radial tire and for the NPT 34 of Figure 4. At a load of 400 kg, the NPT 34 has a cornering stiffness of 70 kg/deg, and the pneumatic tire has a cornering stiffness of 60 kg/deg. This can also be expressed as a cornering coefficient, by dividing the stiffness by the vertical load. Thus, the NPT 34 has a cornering coefficient of 0.175 and the pneumatic tire has a coefficient of 0.15. At higher loads, the NPT 34 lateral stiffness continues to be almost proportional with load. It is almost linear. But, the pneumatic tire stiffness begins to asymptotically approach a value of about 75 kg/deg. At very high loads, the cornering coefficient decrease to about 0.10, or less.

This is a positive attribute for an automotive tire. As a vehicle turns, weight is transferred to the outside tire. If the cornering coefficient is non-linear with load, the vehicle response will not be linear, either. The vehicle may become more understeering, for example. A linear tire will be more easily controlled by a computer algorithm. Thus, it is quite advantageous for an autonomous vehicle to have a cornering coefficient that remains relatively constant with load.

For example, in some embodiments, the cornering coefficient of the non-pneumatic tire 34 at 160% of the rated load of the non-pneumatic tire 34 may be at least 65%, in some cases at least 75%, in some cases at least 80%, and in some cases an even greater percentage of the cornering coefficient of the non-pneumatic tire 34 at 80% of the rated load.

In some embodiments, a design window of tires for autonomous, on-road cars such as the non-pneumatic tire 34 may include:

- the outer diameter D_T of the non-pneumatic tire 34 being between 580 mm and 730 mm;
- the width W_T of the non-pneumatic tire 34 being between 175 mm and 260 mm; and
- the inner diameter D_{TI} of the non-pneumatic tire 34 being between 13 inches (330 mm) and 18 inches (460 mm).

A rated load for tires in this window, such as the rated load of the non-pneumatic tire 34, may be between 400 kg and 900 kg, for sustained operation at 140 kph.

Therefore, in some embodiments, the wheel 20_i, including its non-pneumatic tire 34, may provide a portfolio of performances that enable optimization for the autonomous vehicle 10, such as any of or any combination (including all) of these characteristics:

- the outer diameter D_T of the non-pneumatic tire 34 between 580 mm and 730 mm, and the width W_T of the non-pneumatic tire 34 between 175 mm and 260 mm;
- the rated load of the non-pneumatic tire 34 between 400 kg and 900 kg;
- the hydroplaning speed of the non-pneumatic tire 34 that is at least 90 kph when the tread depth d_t is at the wear indicator (e.g., wear bar height), for a water depth of between 2 and 4 mm, at 80% of the rated load of the non-pneumatic tire 34;
- the rolling resistance coefficient of the non-pneumatic tire 34 that is no more than (i.e., equal to or less than) 0.011 at 80 kph, at 80% of the rated load of the non-pneumatic tire 34;

- the spoke fundamental frequency of the non-pneumatic tire 34 that is no more than (i.e., equal to or less than) 85 Hz, at 80% of the rated load of the non-pneumatic tire 34;
- the normalized spoke energy of the non-pneumatic tire 34 that is no more than (i.e., equal to or less than) 2.3 watts, at 80% of the rated load of the non-pneumatic tire 34;
- the torsional rigidity of the non-pneumatic tire 34 that is at least 11 kN-m / radian, at 80% of the rated load of the non-pneumatic tire 34;
- the lateral rigidity of the non-pneumatic tire 34 that is at least equal to the vertical rigidity of the non-pneumatic tire 34, at 80% of the rated load of the non-pneumatic tire 34; and/or
- the cornering coefficient of the non-pneumatic tire 34 at 160% of the rated load of the non-pneumatic tire 34 that is 65% of the cornering coefficient at 80% of the rated load.

In some embodiments, with additional reference to Figures 23 to 26, the non-pneumatic tire 34 may comprise a plurality of sensors 81_1-81_N to provide information regarding the tire 34 to the controller 80 of the autonomous vehicle 10 in order to allow the controller 80 to perform actions based on the information regarding the tire 34, such as, for example, to communicate the information regarding the tire 34 to a user and/or to control the vehicle 10 based on one or more aspects (e.g., a temperature, a load, a coefficient of friction with the road 11, etc.) of the tire 34. This may be useful, for instance, to gain knowledge about the tire 34, to help prevent rapid wear or other deterioration of the tire 34, and/or to control the speed of the vehicle 10.

Each sensor 81_x is configured to sense a physical characteristic of the non-pneumatic tire 34 and to issue a sensor signal relating to the non-pneumatic tire 34 and derived based on the physical characteristic of the non-pneumatic tire 34 that is sensed. For example, in various embodiments, the sensor 81_x may be:

- an accelerometer (e.g., a 3-axes accelerometer) to sense an acceleration of part of the non-pneumatic tire 34 (e.g., the inner band 33 or another part of the annular beam 36). For instance, the acceleration sensed by the accelerometer may be a radial acceleration at a location on the tire 34 at a known radius from the axis of rotation of the tire 34 so that a (tangential) speed of that location, a rotational speed of that location, a vibration at that location, etc. can be derived;

- a temperature sensor (e.g., a thermocouple, a thermistor, a resistance temperature detector, an infrared sensor) to sense a temperature of part of the non-pneumatic tire 34 (e.g., the annular beam 36);
- a strain sensor to sense a strain within part of the non-pneumatic tire 34 (e.g., the annular beam 36);
- a load sensor (e.g., a load cell, pressure transducer, etc.) to sense a load on part of the non-pneumatic tire 34 (e.g., the tread 50 on the road 11); or
- any other type of sensor.

In this embodiment, the sensor 81_x is disposed within the elastomeric material 45 of the non-pneumatic tire 34. More particularly, in this embodiment, the sensor 81_x is disposed within the elastomeric material 45 of the annular beam 36. In this example, the sensor 81_x is disposed at the inner band 33 of the annular beam 36. In another example, in some embodiments, as shown in Figure 27, the sensor 81_x may be disposed in a given one of the voids 56_1-56_N of the annular beam 36. The sensor 81_x may be relatively small, compared to the void's crosssectional area, and may be mounted in such a manner than localized stresses and strains in the annular beam 36 are not affected.

The sensor 81_x comprises a sensing device 103 to sense the physical characteristic of the non-pneumatic tire 34 and an interface 105 comprising a transmitter 91 for issuing the sensor signal indicative of the physical characteristic of the non-pneumatic tire 34 that is sensed. In this embodiment, the sensor 81_x and the controller 80 of the autonomous vehicle 10 are connected wirelessly such that the transmitter 91 of the sensor 81_x is a wireless transmitter that can wirelessly transmit the sensor signal to a wireless receiver 93 that can wirelessly receive the sensor signal for processing by the controller 80.

The sensor 81_x may be powered in any suitable way. For example, in some embodiments, the sensor 81_x may comprise a power source (e.g., comprising a battery) that stores energy to power the sensor 81_x. Alternatively or additionally, in some embodiments, the sensor 81_x may harvest energy to power itself. For instance, in some embodiments, the sensor 81_x may comprises a piezoelectric element to harvest energy from movement, deformation, pressure, and/or another mechanical effect on material and/or an induction antenna (e.g., using radio-frequency identification (RFID) technology) to harvest energy from a wireless signal.

In some embodiments, respective ones of the sensors 81_1-81_N may be configured to sense the same physical characteristic of the non-pneumatic tire 34. Alternatively, in some embodiments, respective ones of the sensors 81_1-81_N may be configured to sense different physical characteristics of the non-pneumatic tire 34 (e.g., the acceleration, the temperature, etc. of part of the annular beam 36). Also, in some embodiments, only a single sensor such as the sensors 81_1-81_N may be part of the wheel 20_i.

In some cases, a signal from a sensor 81_x may be processed to reveal other one or more variables related to tire performance. For example, in some embodiments, an acceleration signal from a sensor 81_x mounted in the annular beam 36 of the non-pneumatic tire 34 may be processed to provide the length L_c of the contact patch 25 of the non-pneumatic tire 34. Such information may be combined with other known tire characteristics to provide a load on the tire 34.

For example, in some embodiments, the information regarding the non-pneumatic tire 34 provided to the controller 80 of the autonomous vehicle 10 based on the sensors 81_1-81_N of the non-pneumatic tire 34 may include:

a) Kinematic information regarding kinematics of the tire 34. For instance, this may be indicative of a radial acceleration of the tire 34, a number of revolutions of the tire 34, such as a number of revolutions per kilometer of the tire 34 and/or a rotational speed of the tire 34 (e.g., in revolutions per minute (rpm)), and/or any other parameter related to the kinematics of the tire 34. This may allow determination of a distance traveled by the tire 34, an average speed of the tire 34, etc. A sensor 81_x may include an accelerometer to derive this information;

b) Structural information regarding a structure of the tire 34. For instance, this may be indicative of a vibrational signature of the tire 34 such that a crack in the tire 34 (e.g., in a given of the spokes 42_1-42_T) is detectable by detecting a change in the vibrational signature of the tire 34. For example, the controller 80 may monitor vibrational characteristics of the tire 34 and, upon detecting a change in one or more of the vibrational characteristics may deem that a crack is present in the tire 34. A crack in the tire's structure may result in a change in a frequency power spectrum of the tire 34, produced as the tire 34 undergoes normal rolling operation. These changes may be detected by processing the signal from an accelerometer implemented by a sensor 81_x and comparing to established normal values.

c) Temperature information regarding the temperature of the tire 34. A sensor 81_x may include a temperature sensor to derive this information.

The controller 80 of the autonomous vehicle may perform various actions based on the information regarding the non-pneumatic tire 34 derived from the sensors 81_1-81_N of the non-pneumatic tire 34.

For instance, in some embodiments, the controller 80 may control operation of the vehicle 10 based on the information regarding the non-pneumatic tire 34 derived from the sensors 81_1-81_N of the non-pneumatic tire 34. For example, the controller 80 may control the speed of the vehicle 10, such as to limit, reduce and/or allow an increase in the speed of the vehicle 10, based on the information regarding the tire 34 derived from the sensors 81_1-81_N of the tire 34.

As an example, in some embodiments, the controller 80 may control the speed of the vehicle 10, such as to limit, reduce and/or allow an increase in the speed of the vehicle 10, based on the temperature of the tire 34, where a sensor 81_x of the tire 34 includes a temperature sensor. For instance, in some cases, the controller 80 may limit and/or reduce the speed of the vehicle 10 when the temperature of the tire 34 derived from the sensor 81_x reaches a threshold deemed to be associated with degradation of the tire 34 (e.g., performance, wear, etc.).

As another example, in some embodiments, the controller 80 may control the speed of the vehicle 10, such as to limit, reduce and/or allow an increase in the speed of the vehicle 10, based on the load on the tire 34, where a sensor 81_x of the tire 34 includes an accelerometer. For instance, the accelerometer may sense the radial acceleration of the tire 34, which may be used to estimate the length L_C of the contact patch 25 of the tire 34. A contact patch area of a rolling tire is stationary. A continuous signal from an accelerometer directly reveals a time during which the accelerometer is in the contact patch. Multiplying this time by the instantaneous tire translational speed gives an estimate of the contact patch length. Based on its relationship with the length L_c of the contact patch 25 of the tire 34, the load on the tire 34 may be determined by using a known relationship between contact patch length and applied vertical load. Such information is available for any non-pneumatic tire, and may be continuously updated by intelligent communication between vehicle sensor data and tire sensor data. For instance, in some cases, the controller 80 may limit and/or reduce the speed of the vehicle 10 when the load on the tire 34 derived from the sensor 81_x reaches a threshold.

As another example, in some embodiments, the controller 80 may control the speed of the vehicle 10, such as to limit, reduce and/or allow an increase in the speed of the vehicle 10, based on an environment of the tire 34. For instance, in some embodiments, the controller 80 may control the speed of the vehicle 10, such as to limit, reduce and/or allow an increase in the speed of the vehicle 10, based on a coefficient of friction of the tire 34 on the road 11, where a sensor 81_x of the tire 34 includes an accelerometer. For instance, the accelerometer may sense the radial acceleration of the tire 34, which may be used to estimate the coefficient of friction of the tire 34 on the road 11. The controller 80 may store reference data associating values of radial acceleration of the tire 34 with values of friction coefficient between the tire 34 and the road 11. This reference data may be obtained empirically or by machine learning as the vehicle 10 travels over road surfaces of known coefficient of friction, and a radial acceleration behavior of the tire 34 on such road surfaces is monitored. For example, in some cases, the controller 80 may limit and/or reduce the speed of the vehicle 10 when the coefficient of friction of the tire 34 on the road 11 derived from the sensor 81_x reaches a threshold.

Although in embodiments considered above the road vehicle 10 is autonomous, in other embodiments, the road vehicle 10 may be a non-autonomous vehicle without any autonomous driving capability.

Also, while in embodiments considered above, the road vehicle 10 is an automobile, in other embodiments, the road vehicle 10 may be a truck (e.g., an autonomous truck), a bus (e.g., an autonomous bus), or any other road vehicle.

Certain additional elements that may be needed for operation of some embodiments have not been described or illustrated as they are assumed to be within the purview of those of ordinary skill in the art. Moreover, certain embodiments may be free of, may lack and/or may function without any element that is not specifically disclosed herein.

Any feature of any embodiment discussed herein may be combined with any feature of any other embodiment discussed herein in some examples of implementation.

In case of any discrepancy, inconsistency, or other difference between terms used herein and terms used in any document incorporated by reference herein, meanings of the terms used herein are to prevail and be used.

Although various embodiments and examples have been presented, this was for purposes of describing, but is not limiting. Various modifications and enhancements will become apparent to those of ordinary skill in the art.

CLAIMS

1. A wheel comprising a non-pneumatic tire for an autonomous vehicle on a road, the non-pneumatic tire comprising:
   - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
   - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road.

2. The wheel of claim 1, wherein, at 80% of a rated load of the non-pneumatic tire: a rolling resistance coefficient of the non-pneumatic tire is no more than 0.012; and a torsional stiffness of the non-pneumatic tire is at least 11000 N-m / radian.

3. The wheel of claim 1, wherein: the annular support comprises a plurality of spokes extending radially inwardly from the annular beam towards an axis of rotation of the non-pneumatic tire and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above the axis of rotation of the non-pneumatic tire are in tension; and, at 80% of a rated load of the non-pneumatic tire: a fundamental frequency of each of the spokes is no more than 65 Hz; a normalized power of each of the spokes is no more than 2 watts; and a torsional stiffness of the non-pneumatic tire is at least 11000 N-m / radian.

4. The wheel of claim 1, wherein a noise level in a cabin of the vehicle at a given speed of the vehicle is at least 1 dB lower when the vehicle is equipped with the non-pneumatic tire than if the vehicle was instead equipped with a pneumatic wheel comprising an equivalent commercially-available pneumatic tire that would replace the wheel.

5. The wheel of claim 1, comprising a tread disposed radially outwardly of the annular beam, wherein, at a given load on the non-pneumatic tire and a given water depth

on the road, a hydroplaning speed of the non-pneumatic tire when the tread is at a tread wear indicator of the non-pneumatic tire is at least 85% of the hydroplaning speed of the non-pneumatic tire at a full depth of the tread.

6. The wheel of claim 1, wherein, at 80% of a rated load of the non-pneumatic tire, a hydroplaning speed of the non-pneumatic tire at 3 mm of tread depth is at least 85% of the hydroplaning speed of the non-pneumatic tire at full tread depth, when water depth is between 3 and 4 mm.

7. The wheel of claim 1, comprising: a tread disposed radially outwardly of the annular beam; and an outer circumferential channel that is deeper than a tread depth of the tread.

8. The wheel of claim 7, wherein the outer circumferential channel extends between lateral parts of the non-pneumatic tire that respectively comprise lateral parts of the annular beam and lateral parts of the tread.

9. The wheel of claim 8, wherein: the annular beam comprises an outer annular portion, an inner annular portion, and a shearing annular portion between the outer annular portion and the inner annular portion of the annular beam; and the lateral parts of the annular beam respectively comprise lateral parts of the inner annular portion, lateral parts of the shearing annular portion, and lateral parts of the outer annular portion of the annular beam.

10. The wheel of claim 8, wherein: the annular beam comprises a plurality of voids distributed in a circumferential direction of the annular beam and the lateral parts of the annular beam include respective ones of the voids extending therethrough.

11. The wheel of claim 10, wherein the voids of the annular beam extend transversally to an axial direction of the non-pneumatic tire.

12. The wheel of claim 8, wherein the outer circumferential channel is disposed substantially centrally in an axial direction of the non-pneumatic tire.

13. The wheel of claim 8, wherein the outer circumferential channel extends continuously around the non-pneumatic tire.

14. The wheel of claim 1, wherein, at 80% of a rated load of the non-pneumatic tire: a gross contact pressure at the contact patch of the non-pneumatic tire is at least 0.25 MPa; and a vertical stiffness of the non-pneumatic tire is no more than 32 kg/mm.

15. The wheel of claim 1, wherein a cornering coefficient of the non-pneumatic tire at 160% of a rated load of the non-pneumatic tire is at least 65% of the cornering coefficient of the non-pneumatic tire at 80% of the rated load of the non-pneumatic tire.

16. The wheel of claim 1, wherein: the annular support comprises a plurality of spokes extending radially inwardly from the annular beam to a hub and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above an axis of rotation of the non-pneumatic tire are in tension; and a distance between a point of intersection of a given one of the spokes with the annular beam and a point of intersection of the given one of the spokes with the hub is at least 115% of a radial distance from an outer radial extent of the hub to an inner radial extent of the annular beam.

17. The wheel of claim 1, wherein: the annular support comprises a plurality of spokes extending radially inwardly from the annular beam towards an axis of rotation of the non-pneumatic tire and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above the axis of rotation of the non-pneumatic tire are in tension; the non-pneumatic tire comprises a tread

disposed radially outwardly of the annular beam; and the non-pneumatic tire is characterized by any of or any combination of:

- an outer diameter between 580 mm and 730 mm, and a width between 190 mm and 260 mm;
- a rated load between 380 kg and 900 kg;
- a hydroplaning speed of at least 90 kph when a tread depth is at a wear bar height of the tread, for a water depth of between 2 and 4 mm, at 80% of the rated load of the non-pneumatic tire;
- a rolling resistance coefficient of no more than 0.011 at 80 kph, at 80% of the rated load of the non-pneumatic tire;
- a fundamental frequency of each of the spokes of no more than 85 Hz, at 80% of the rated load of the non-pneumatic tire;
- a normalized power of each of the spokes that is no more than 2.3 watts, at 80% of the rated load of the non-pneumatic tire;
- a torsional rigidity of at least 1.1 kN-m / radian, at 80% of the rated load of the non-pneumatic tire;
- a lateral rigidity that is at least equal to a vertical rigidity, at 80% of the rated load of the non-pneumatic tire; and
- a cornering coefficient at 160% of the rated load of the non-pneumatic tire that is at least 65% of the cornering coefficient at 80% of the rated load of the non-pneumatic tire.

18. The wheel of claim 1, wherein: when the non-pneumatic tire is loaded, an upper portion of the annular support above an axis of rotation of the non-pneumatic tire is in tension; and the non-pneumatic tire comprises a sensor.

19. The wheel of claim 1, wherein the annular beam is configured to deflect more by shearing than by bending at the contact patch of the non-pneumatic tire.

20. The wheel of claim 19, wherein the annular beam comprises an outer annular portion, an inner annular portion, and a shearing annular portion between the outer annular portion and the inner annular portion of the annular beam.

21. The wheel of claim 20, wherein each of the outer annular portion and the inner annular portion of the annular beam is free of substantially inextensible reinforcement running in a circumferential direction of the annular beam.

22. The wheel of claim 1, wherein the annular beam is free of substantially inextensible reinforcement running in a circumferential direction of the annular beam.

23. The wheel of claim 22, wherein the annular beam comprises a plurality of voids distributed in a circumferential direction of the annular beam and arranged to cause the annular beam to deflect more by shearing than by bending at the contact patch of the non-pneumatic tire.

24. The wheel of claim 1, wherein: the annular support comprises a plurality of spokes extending radially inwardly from the annular beam towards an axis of rotation of the non-pneumatic tire and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above the axis of rotation of the non-pneumatic tire are in tension; and first ones of the spokes are spaced from second ones of the spokes in an axial direction of the non-pneumatic tire and are oriented differently than the second ones of the spokes.

25. The wheel of claim 24, wherein the first ones of the spokes are oriented in a same way and the second ones of the spokes are oriented in a same way.

26. The wheel of claim 24, wherein the first ones of the spokes are oriented opposite to the second ones of the spokes.

27. The wheel of claim 1, wherein: the annular support comprises a plurality of spokes extending radially inwardly from the annular beam towards an axis of rotation of the non-pneumatic tire and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above the axis of rotation of the non-pneumatic tire are in tension; and first ones of the spokes are spaced from second ones of the spokes in an axial direction of the non-pneumatic tire and are configured to operate independently from the second ones of the spokes.

28. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
    - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road;

    wherein, at 80% of a rated load of the non-pneumatic tire: a rolling resistance coefficient of the non-pneumatic tire is no more than 0.012; and a torsional stiffness of the non-pneumatic tire is at least 11000 N-m / radian.

29. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
    - a plurality of spokes extending radially inwardly from the annular beam towards an axis of rotation of the non-pneumatic tire and configured to resiliently deform as the non-pneumatic tire engages the road such that upper ones of the spokes above the axis of rotation of the non-pneumatic tire are in tension;

    wherein, at 80% of a rated load of the non-pneumatic tire: a fundamental frequency of each of the spokes is no more than 65 Hz; a normalized power of each of the spokes is no more than 2 watts; and a torsional stiffness of the non-pneumatic tire is at least 11000 N-m / radian.

30. A set of non-pneumatic wheels for a vehicle on a road, each of the non-pneumatic wheels comprising a non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
    - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road;

    wherein a noise level in a cabin of the vehicle at a given speed of the vehicle is at least 1 dB lower when the vehicle is equipped with the non-pneumatic tire of each of the non-pneumatic wheels than if the vehicle was instead equipped with an equivalent commercially-available pneumatic tire at each of an equivalent set of pneumatic wheels that would replace the non-pneumatic wheels.

31. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road;
    - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road; and
    - a tread disposed radially outwardly of the annular beam;

    wherein, at a given load on the non-pneumatic tire and a given water depth on the road, a hydroplaning speed of the non-pneumatic tire when the tread is at a tread wear indicator of the non-pneumatic tire is at least 85% of the hydroplaning speed of the non-pneumatic tire at a full depth of the tread.

32. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and

- an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road;

wherein, at 80% of a rated load of the non-pneumatic tire, a hydroplaning speed of the non-pneumatic tire at 3 mm of tread depth is at least 85% of the hydroplaning speed of the non-pneumatic tire at full tread depth, when water depth is between 3 and 4 mm.

33. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road;
    - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road; and
    - a tread disposed radially outwardly of the annular beam;

    wherein the non-pneumatic tire comprises an outer circumferential channel that is deeper than a tread depth of the tread.

34. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
    - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road;

    wherein, at 80% of a rated load of the non-pneumatic tire: a gross contact pressure at the contact patch of the non-pneumatic tire is at least 0.25 MPa; and a vertical stiffness of the non-pneumatic tire is no more than 32 kg/mm.

35. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:

- an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
- an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road;

wherein a cornering coefficient of the non-pneumatic tire at 160% of a rated load of the non-pneumatic tire is at least 65% of the cornering coefficient of the non-pneumatic tire at 80% of the rated load of the non-pneumatic tire.

36. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road; and
    - a plurality of spokes extending radially inwardly from the annular beam to a hub and configured to resiliently deform as the non-pneumatic tire engages the road;

    wherein a distance between a point of intersection of a given one of the spokes with the annular beam and a point of intersection of the given one of the spokes with the hub is at least 115% of a radial distance from an outer radial extent of the hub to an inner radial extent of the annular beam.

37. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road;
    - a plurality of spokes extending radially inwardly from the annular beam to a hub and configured to resiliently deform as the non-pneumatic tire engages the road; and
    - a tread disposed radially outwardly of the annular beam;

    wherein the non-pneumatic tire is characterized by any of or any combination of:
    - an outer diameter between 580 mm and 730 mm, and a width between 190 mm and 260 mm;

- a rated load between 380 kg and 900 kg;
- a hydroplaning speed of at least 90 kph when a tread depth is at a wear bar height of the tread, for a water depth of between 2 and 4 mm, at 80% of the rated load of the non-pneumatic tire;
- a rolling resistance coefficient of no more than 0.011 at 80 kph, at 80% of the rated load of the non-pneumatic tire;
- a fundamental frequency of each of the spokes of no more than 85 Hz, at 80% of the rated load of the non-pneumatic tire;
- a normalized power of each of the spokes that is no more than 2.3 watts, at 80% of the rated load of the non-pneumatic tire;
- a torsional rigidity of at least 1.1 kN-m / radian, at 80% of the rated load of the non-pneumatic tire;
- a lateral rigidity that is at least equal to a vertical rigidity, at 80% of the rated load of the non-pneumatic tire; and
- a cornering coefficient at 160% of the rated load of the non-pneumatic tire that is at least 65% of the cornering coefficient at 80% of the rated load of the non-pneumatic tire.

38. A wheel comprising a non-pneumatic tire for a vehicle on a road, the non-pneumatic tire comprising:
    - an annular beam configured to deflect at a contact patch of the non-pneumatic tire with the road;
    - an annular support disposed radially inwardly of the annular beam and configured to resiliently deform as the non-pneumatic tire engages the road such that, when the non-pneumatic tire is loaded, an upper portion of the annular support above an axis of rotation of the non-pneumatic tire is in tension; and
    - a sensor.

39. A vehicle comprising a wheel as claimed in any preceding claim.

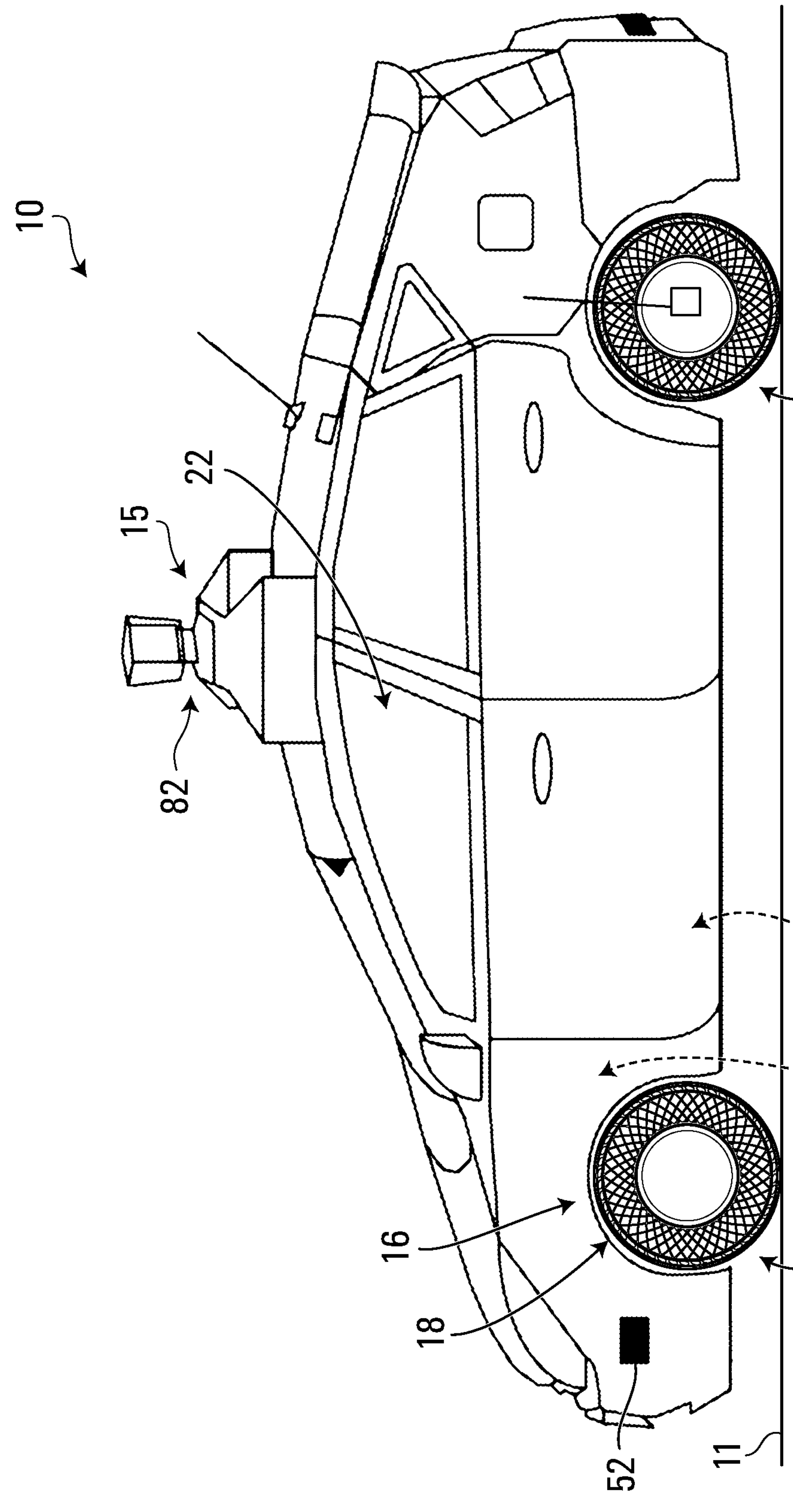

FIG. 1

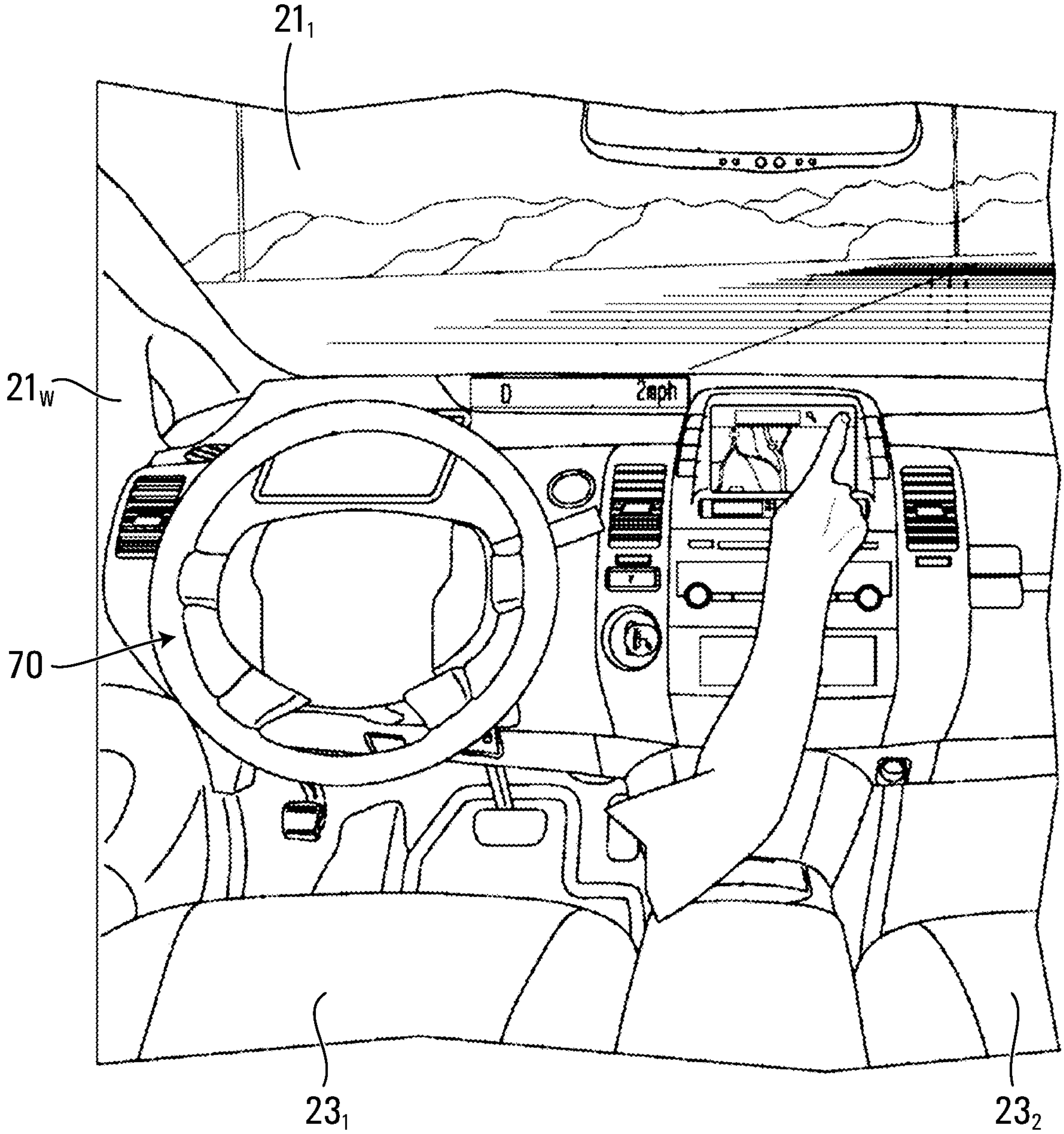

FIG. 2

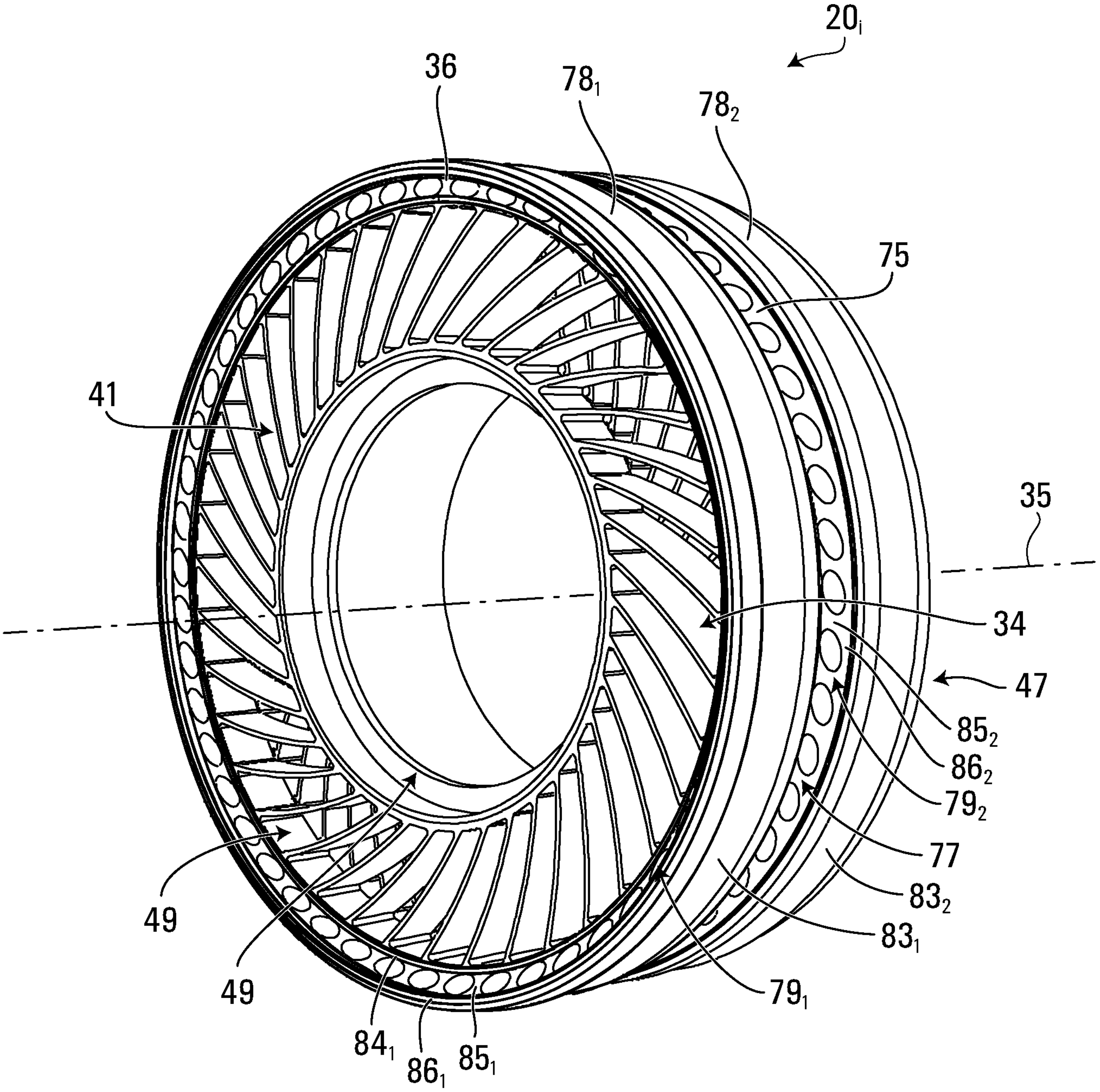
20_i
36
78_1
78_2
75
41
35
34
47
85_2
86_2
79_2
77
83_2
83_1
79_1
49
49
84_1
86_1
85_1

FIG. 4

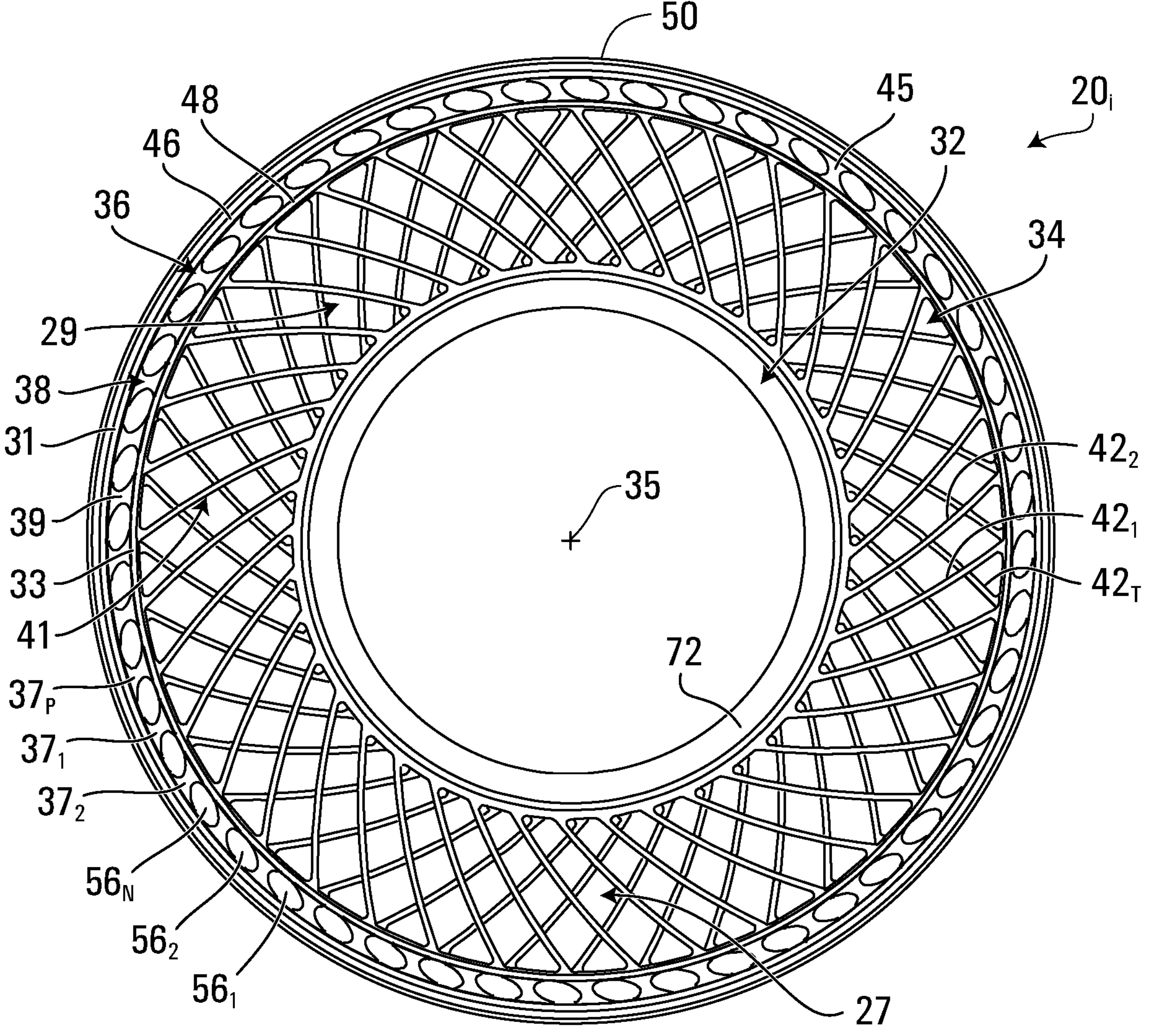
50
48
46
45
36
32
20_i
34
29
38
31
39
33
41
35
42_2
42_1
42_T
72
37_P
37_1
37_2
56_N
56_2
56_1
27

FIG. 5

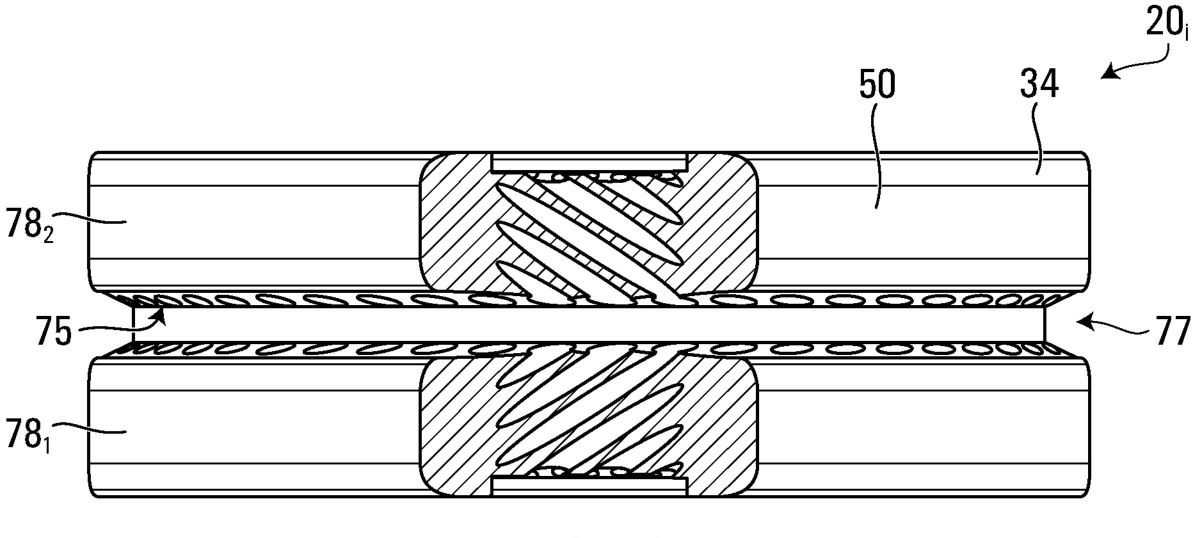
20_i
50
34
78_2
75
77
78_1

FIG. 6

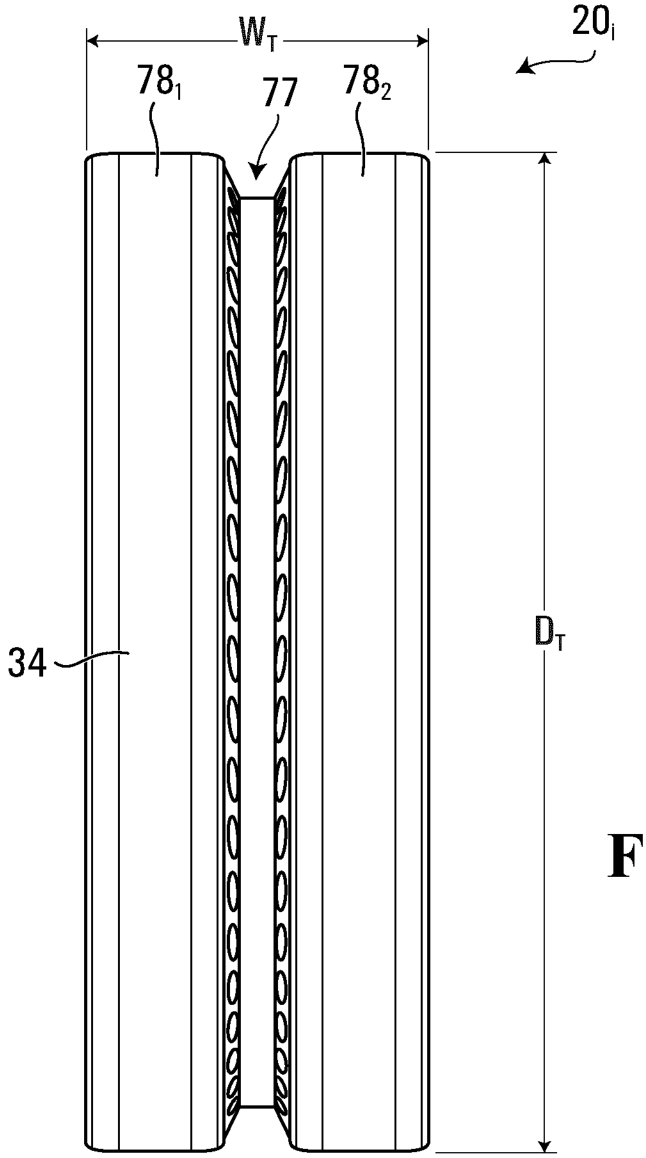

FIG. 7

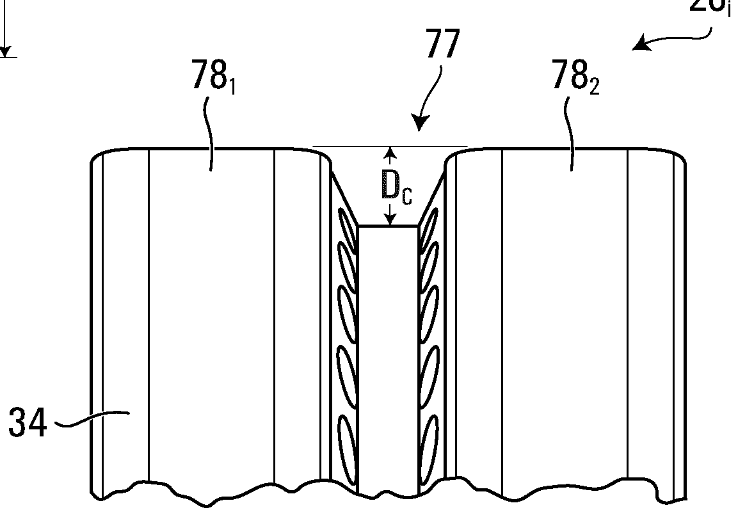

FIG. 8

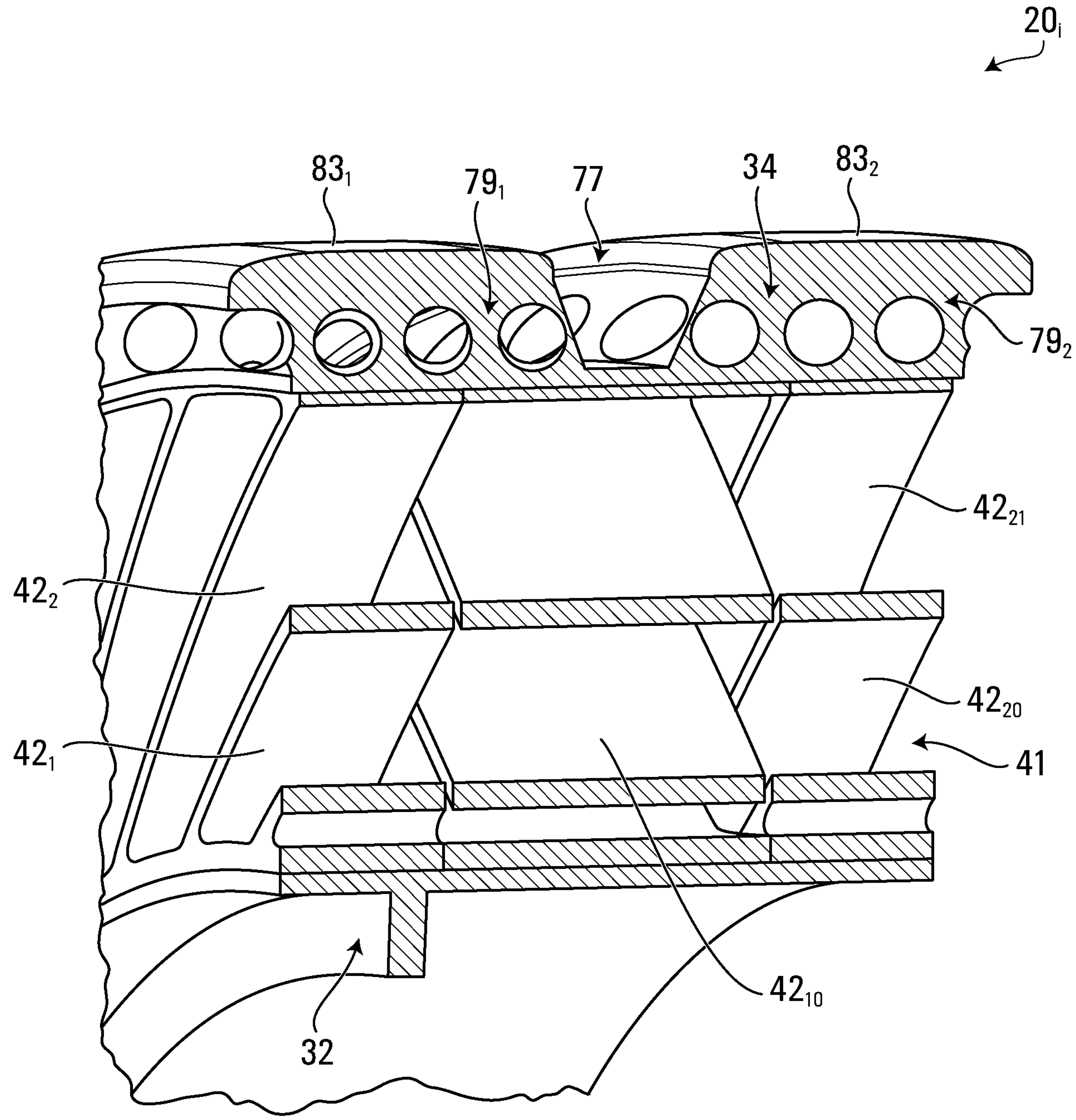

FIG. 9

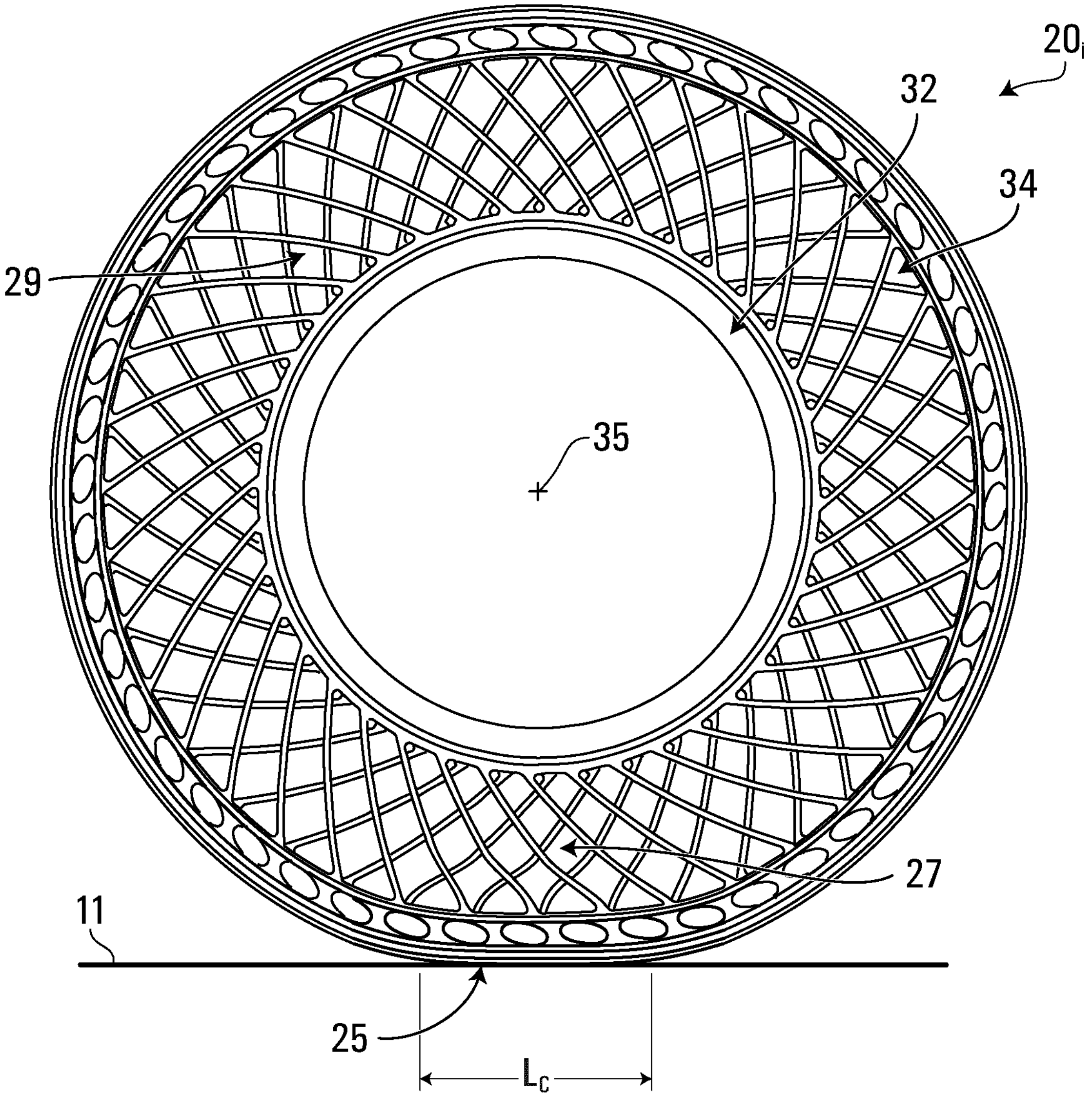

FIG. 10

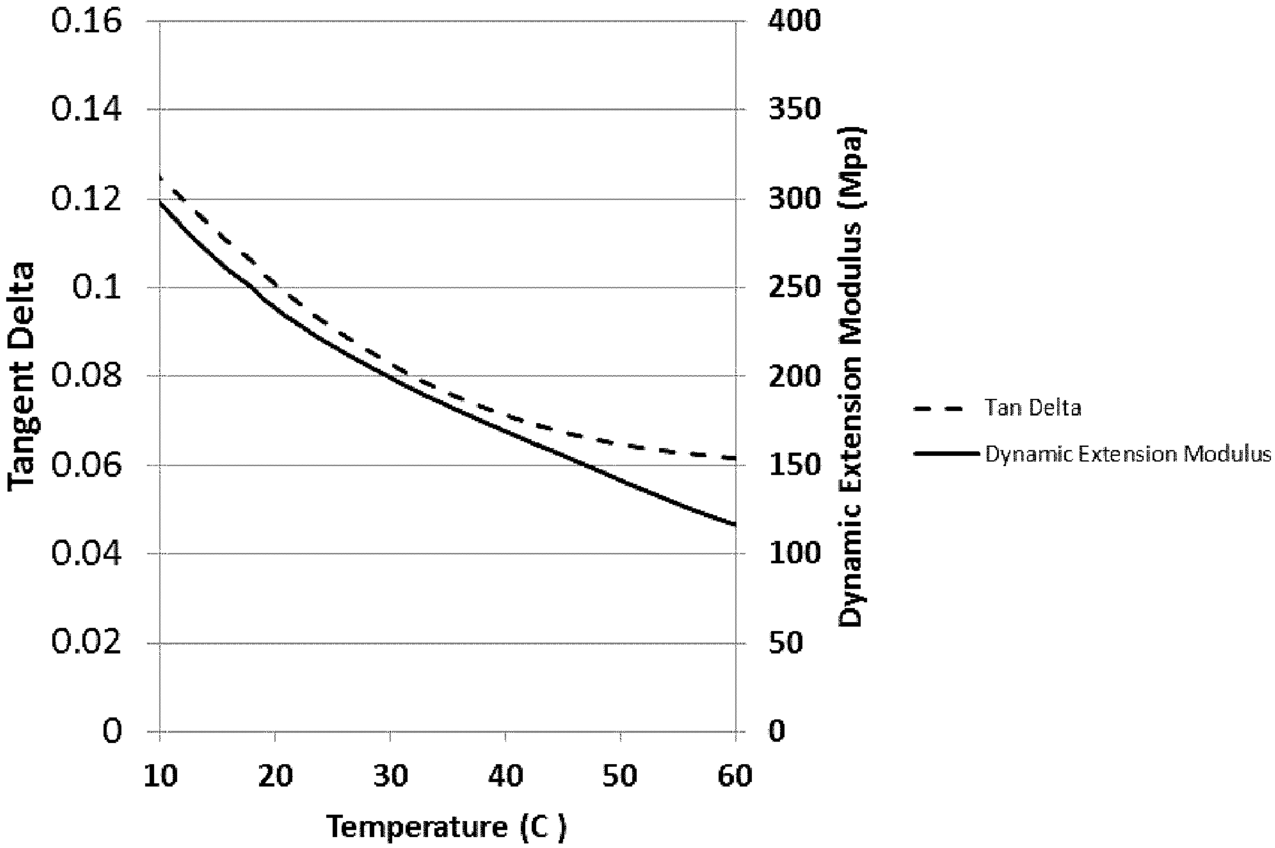
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Tangent Delta
400
350
300
250
200
150
100
50
0
Dynamic Extension Modulus (Mpa)
10
20
30
40
50
60
Temperature (C)
Tan Delta
Dynamic Extension Modulus

FIG. 11

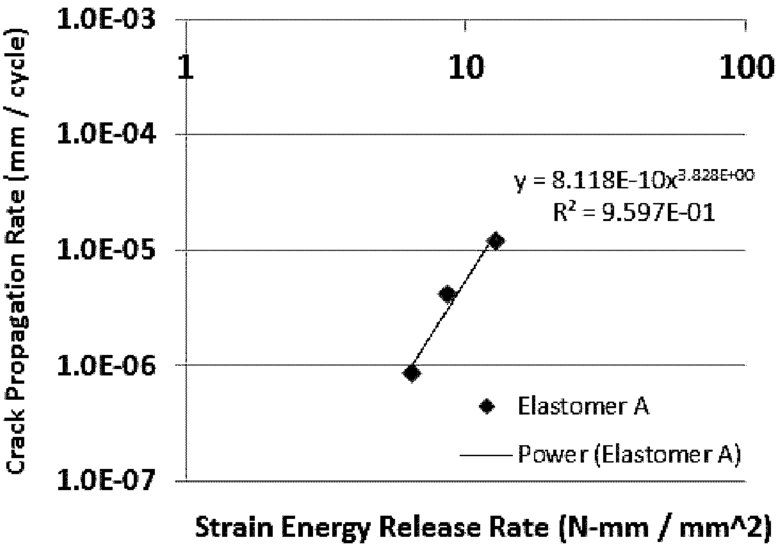
1.0E-03
1.0E-04
1.0E-05
1.0E-06
1.0E-07
Crack Propagation Rate (mm / cycle)
1
10
100
y = 8.118E-10x^3.828E+00
R^2 = 9.597E-01
Elastomer A
Power (Elastomer A)
Strain Energy Release Rate (N-mm / mm^2)

FIG. 12

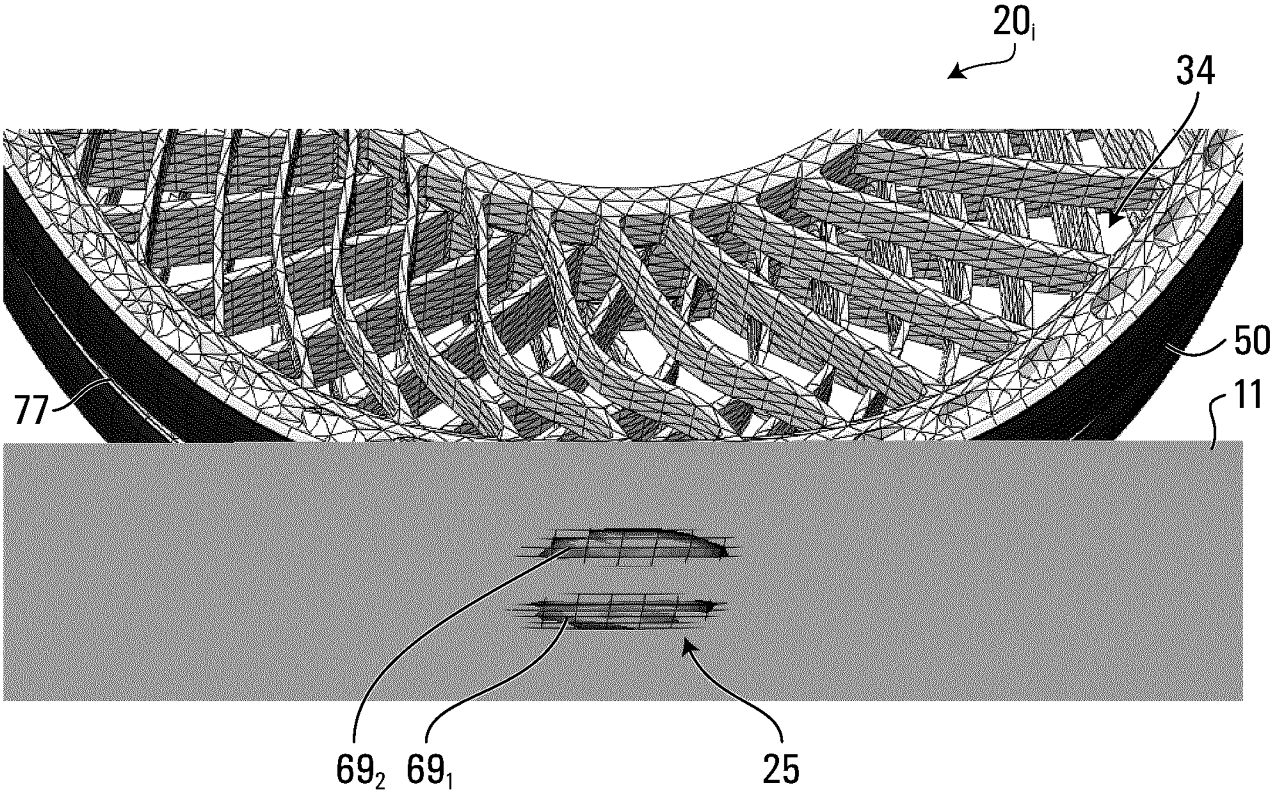
20_i
34
50
11
77
69_2
69_1
25

FIG. 13

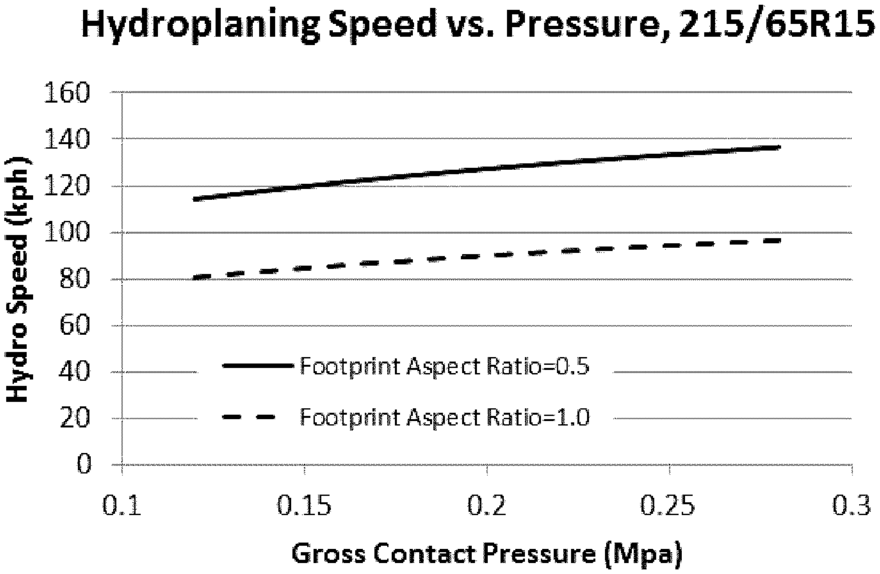
Hydroplaning Speed vs. Pressure, 215/65R15
Hydro Speed (kph)
160
140
120
100
80
60
40
20
0
0.1
0.15
0.2
0.25
0.3
Gross Contact Pressure (Mpa)
Footprint Aspect Ratio=0.5
Footprint Aspect Ratio=1.0

FIG. 14

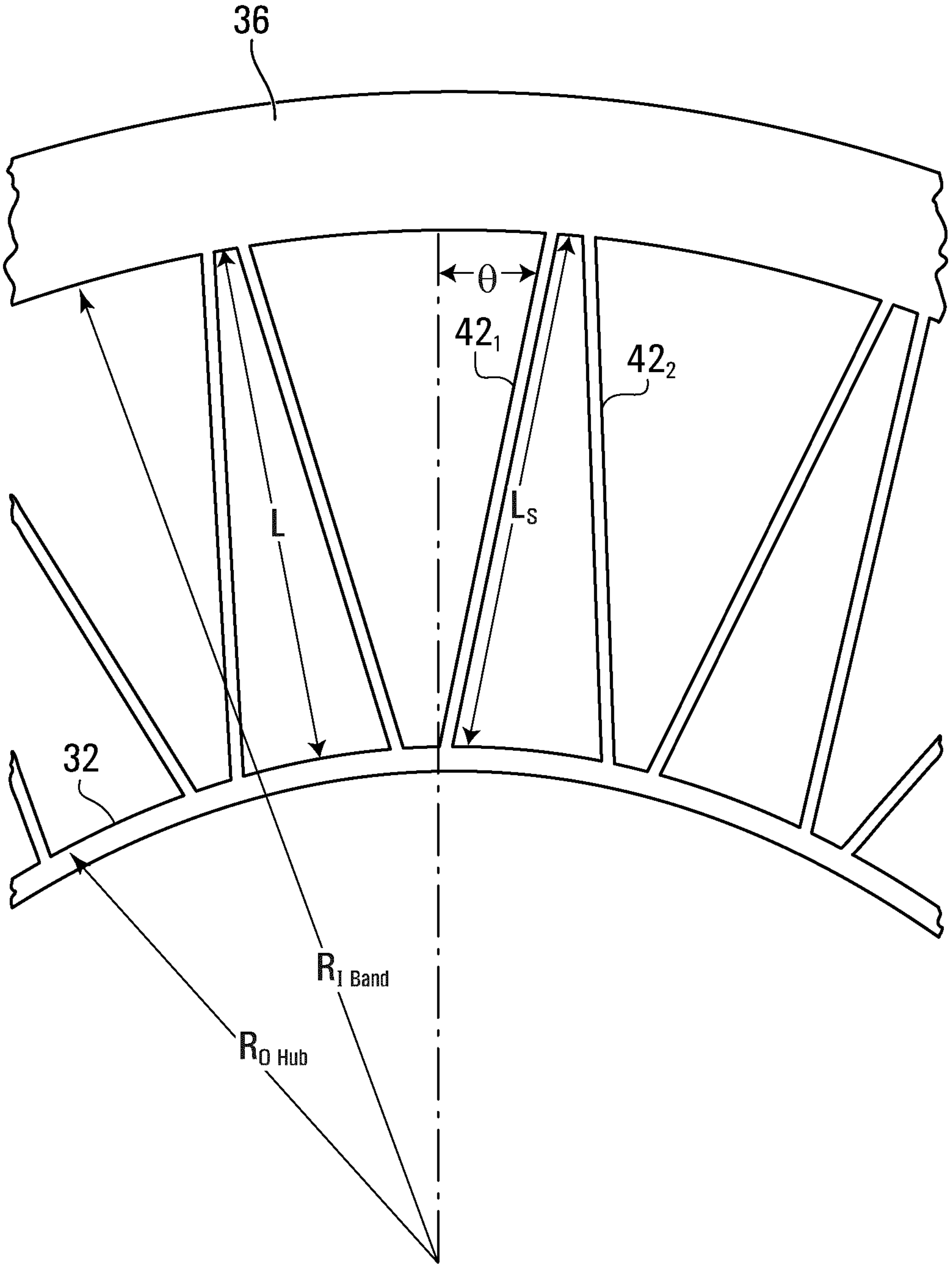

FIG. 15

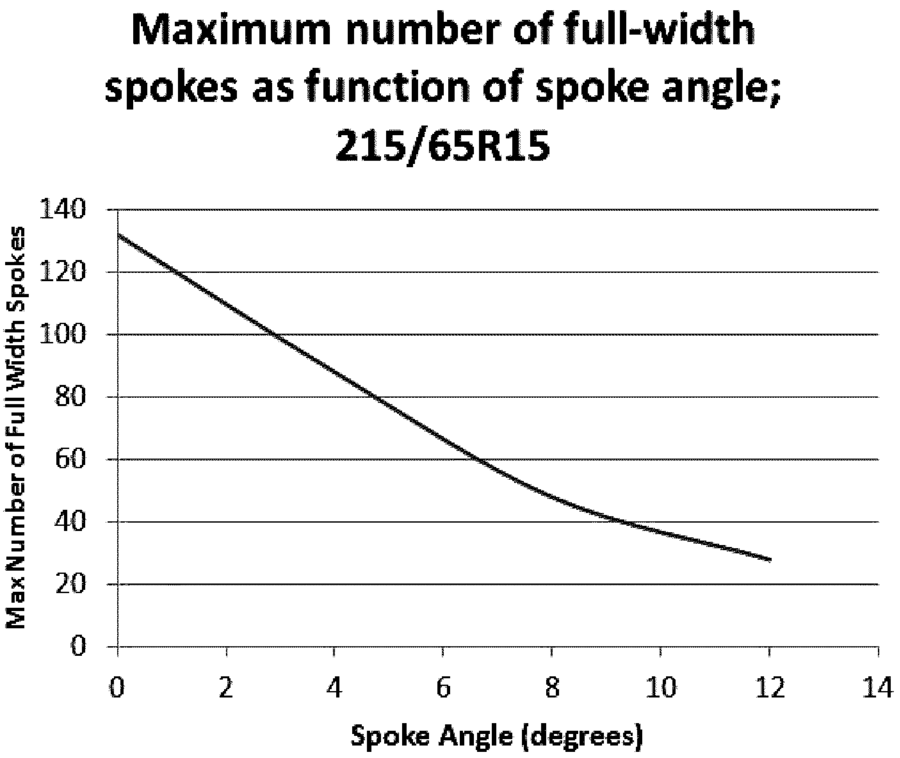
Maximum number of full-width spokes as function of spoke angle; 215/65R15
Max Number of Full Width Spokes
140
120
100
80
60
40
20
0
0
2
4
6
8
10
12
14
Spoke Angle (degrees)

FIG. 16

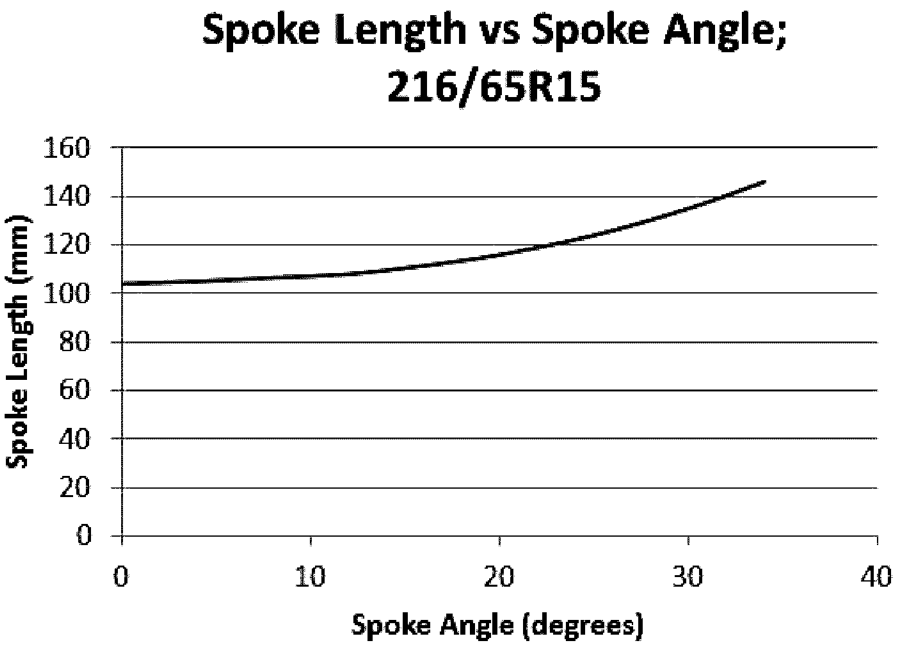
Spoke Length vs Spoke Angle; 216/65R15
Spoke Length (mm)
160
140
120
100
80
60
40
20
0
0
10
20
30
40
Spoke Angle (degrees)

FIG. 17

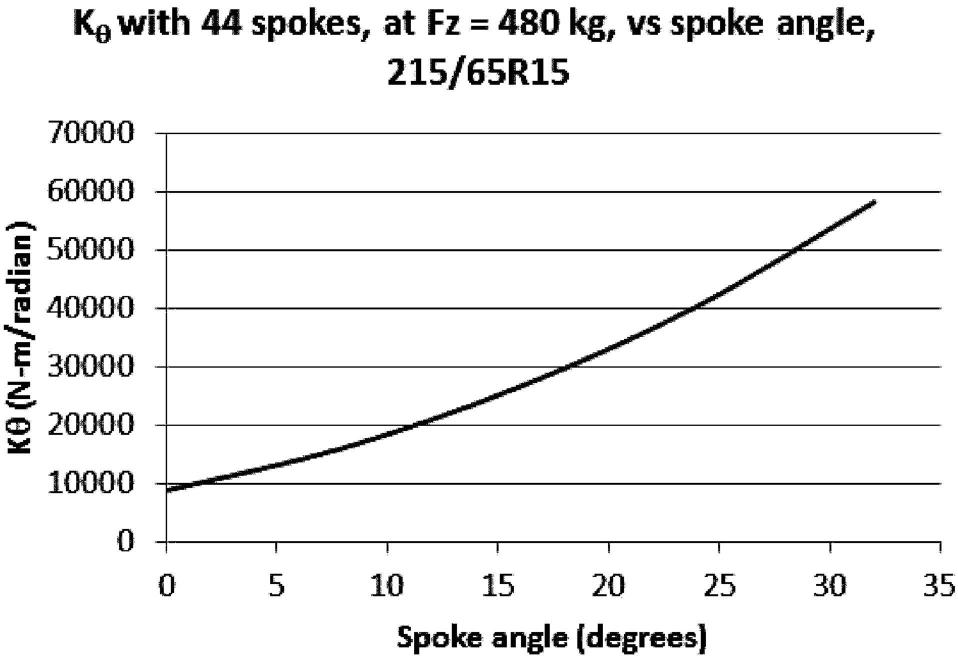
K_θ with 44 spokes, at Fz = 480 kg, vs spoke angle, 215/65R15
Kθ (N-m/radian)
70000
60000
50000
40000
30000
20000
10000
0
0
5
10
15
20
25
30
35
Spoke angle (degrees)

FIG. 18

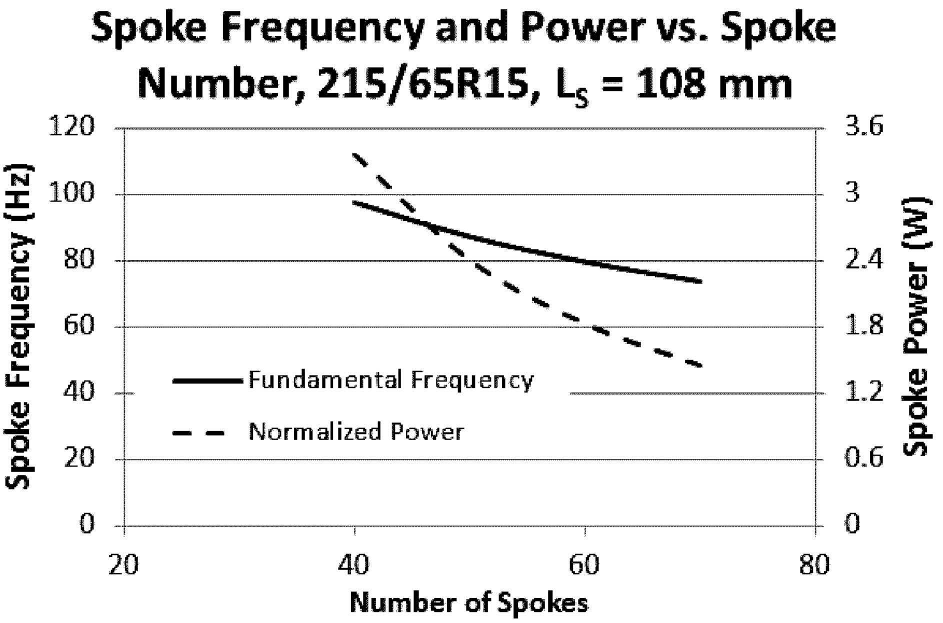
Spoke Frequency and Power vs. Spoke Number, 215/65R15, L_S = 108 mm
Spoke Frequency (Hz)
120
100
80
60
40
20
0
Spoke Power (W)
3.6
3
2.4
1.8
1.2
0.6
0
20
40
60
80
Number of Spokes
Fundamental Frequency
Normalized Power

FIG. 19

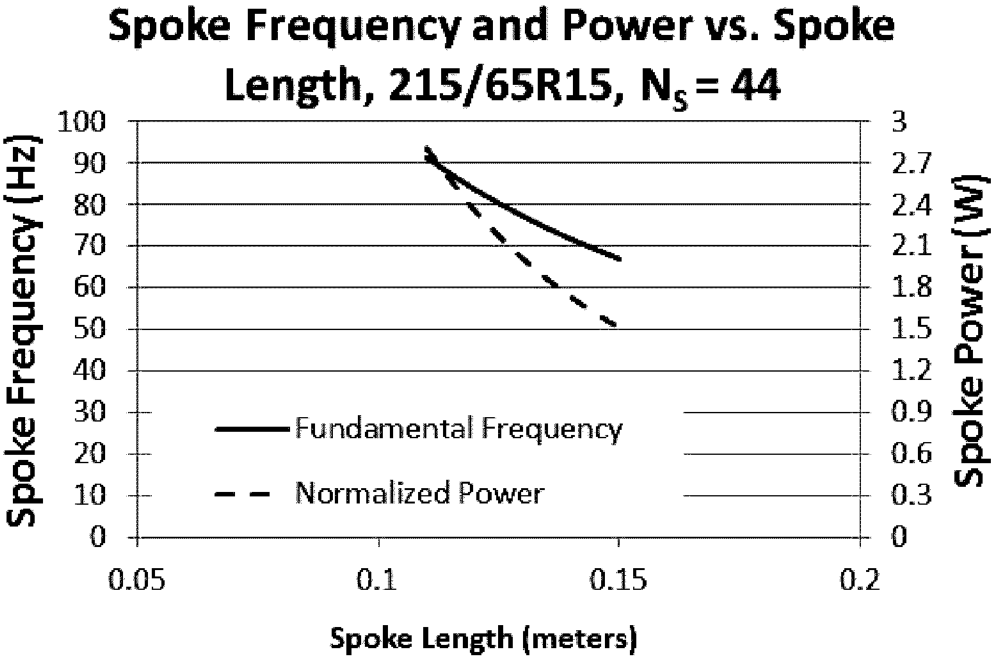
Spoke Frequency and Power vs. Spoke Length, 215/65R15, N_S = 44
Spoke Frequency (Hz)
100
90
80
70
60
50
40
30
20
10
0
3
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0
Spoke Power (W)
Fundamental Frequency
Normalized Power
0.05
0.1
0.15
0.2
Spoke Length (meters)

FIG. 20

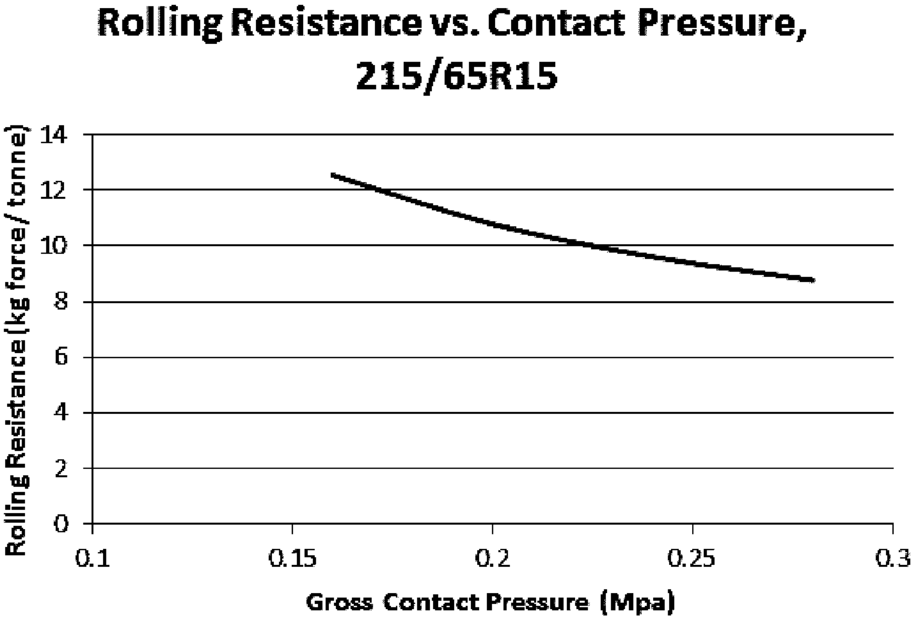
Rolling Resistance vs. Contact Pressure, 215/65R15
Rolling Resistance (kg force/ tonne)
14
12
10
8
6
4
2
0
0.1
0.15
0.2
0.25
0.3
Gross Contact Pressure (Mpa)

FIG. 21

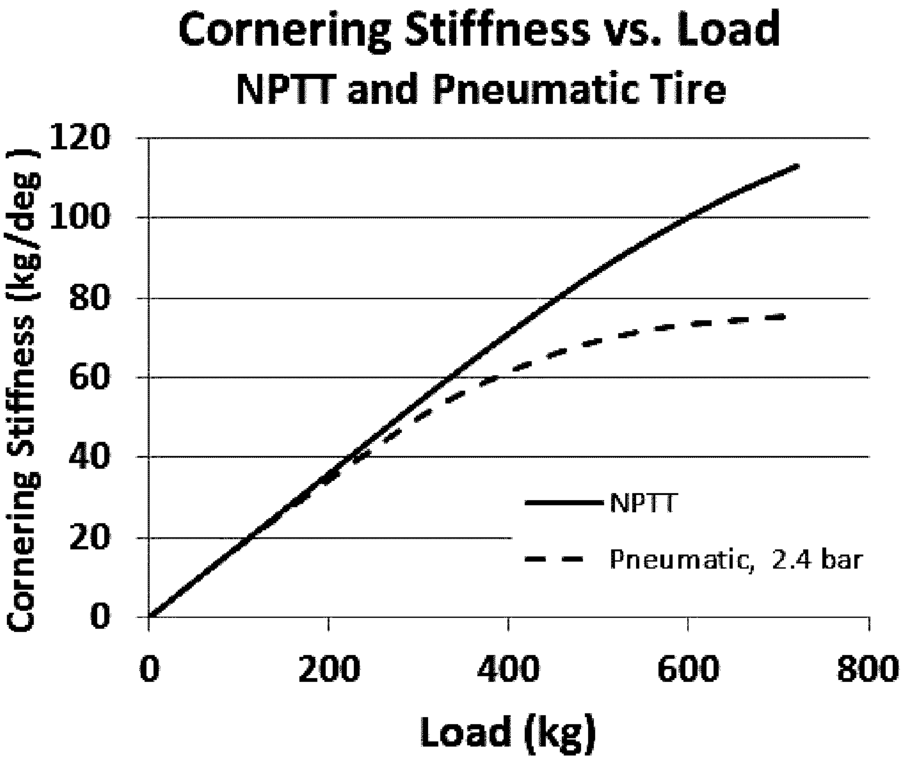
Cornering Stiffness vs. Load
NPTT and Pneumatic Tire
Cornering Stiffness (kg/deg)
120
100
80
60
40
20
0
0
200
400
600
800
Load (kg)
NPTT
Pneumatic, 2.4 bar

FIG. 22

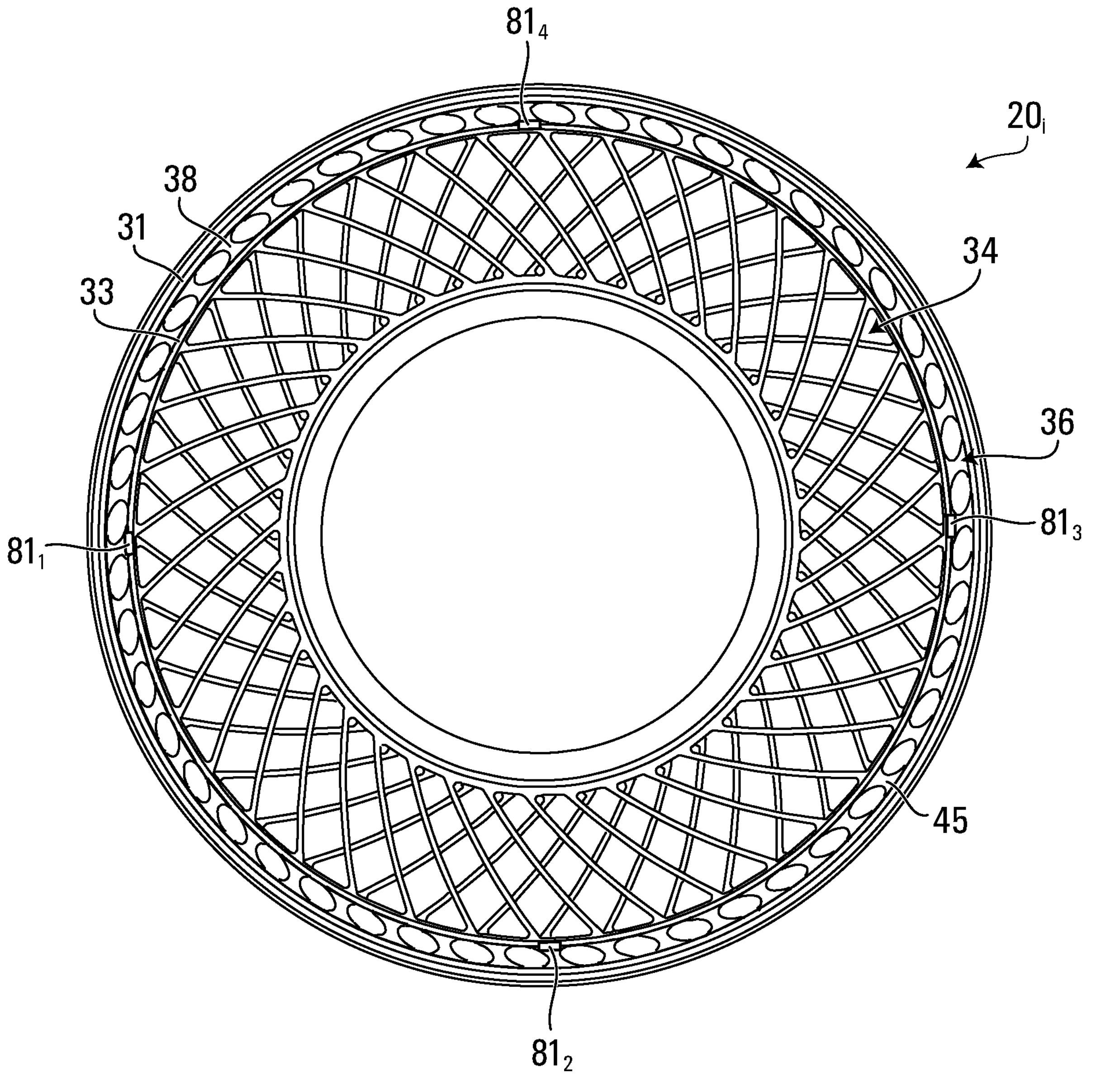

FIG. 23

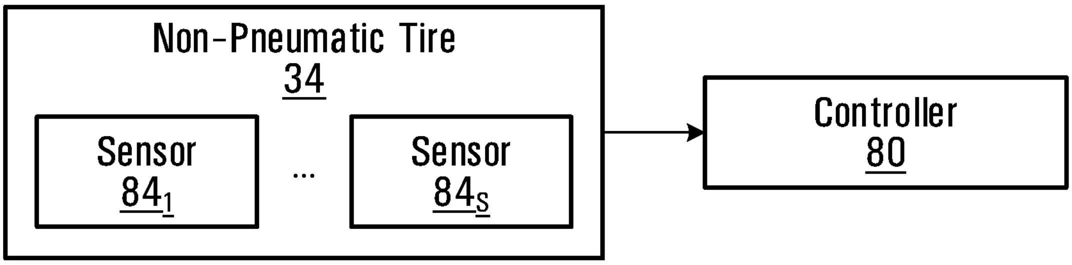

FIG. 24

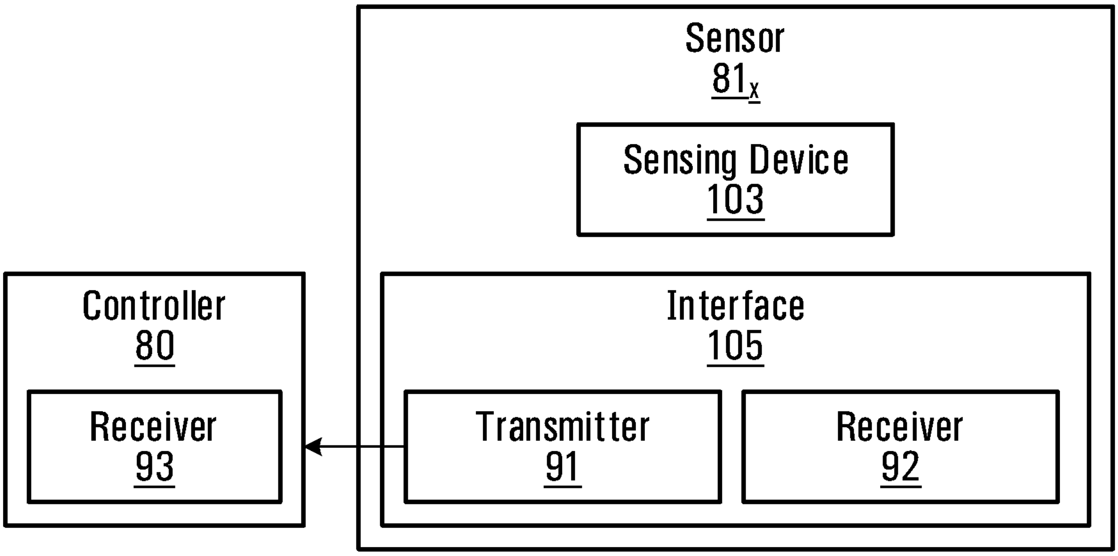

FIG. 25

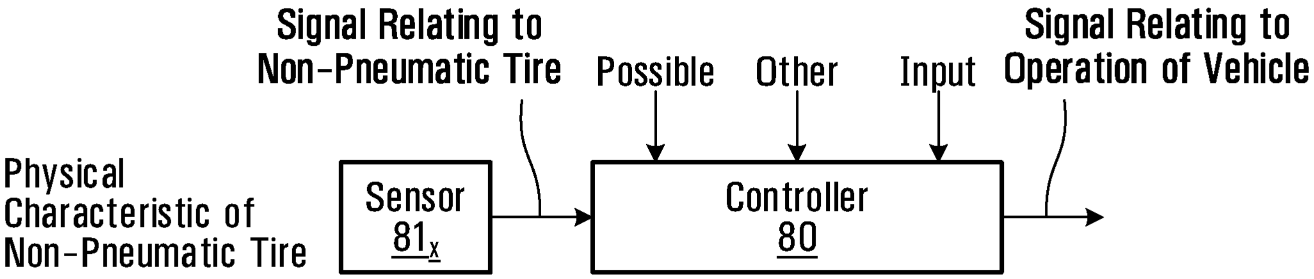

FIG. 26

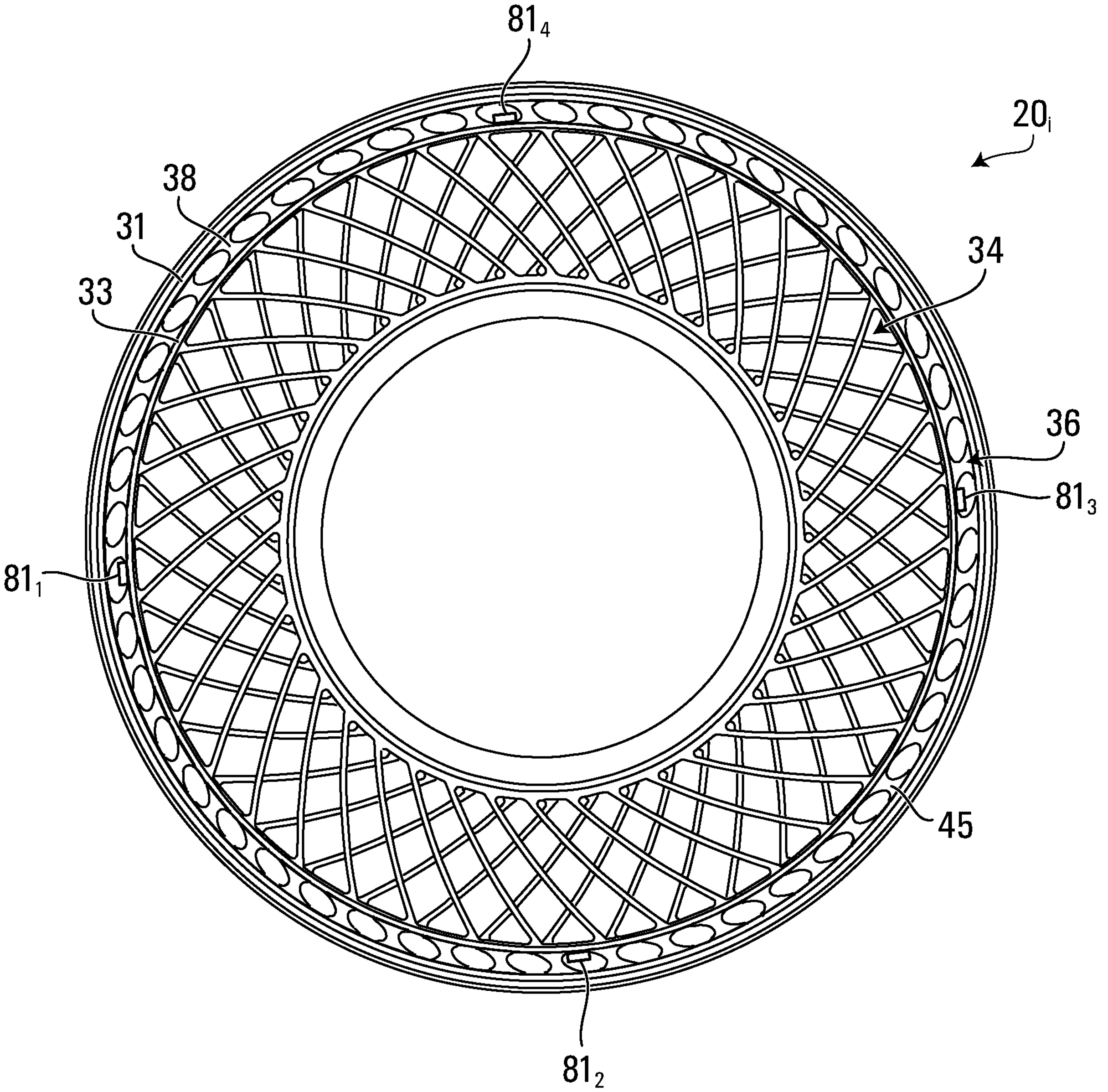

FIG. 27

INTERNATIONAL SEARCH REPORT

International application No.
PCT/CA2019/050722

A. CLASSIFICATION OF SUBJECT MATTER
IPC: ***B60C 9/02*** (2006.01) , ***B60C 7/10*** (2006.01)

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)
IPC(2006): B60C 9/02, B60C 7/10

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

Electronic database(s) consulted during the international search (name of database(s) and, where practicable, search terms used)
Databases: Canadian Patent Database (CPD), Questel Orbit
Keywords: frequency, hydroplaning, central, channel, autonomous, self driving

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US2014367007A1 (THOMPSON, R.) 18 December 2014 (18-12-2014) *Abstract; Fig. 2, 3, 12, 14 and 15*	1 - 6, 14 – 23, 28- 32 and 34 – 39 7 – 13, 24 – 27 and 33
Y	US6095216A (CENNI, R. et al.) 01 August 2000 (01-08-2000) *Abstract; Fig. 1 and 2*	7 – 13 and 33
Y	US2016167434A1 (NISHIDA, M. et al.) 16 June 2016 (16-06-2016) *Fig. 1 *	24 - 27
A	US8646497B2 (CRON, S. M.) 11 February 2014 (11-02-2014) *The whole document*	
A	CA2651523A1 (CRON, S. M.) 27 March 2008 (27-03-2008) *The whole document*	
A	CA2458002A1, (RHYNE, T. B. et al.) 6 March 2003 (06-03-2003) *The whole document*	

☐ Further documents are listed in the continuation of Box C.　☑ See patent family annex.

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