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(54) SYSTEM AND METHOD FOR MONITORING TIRES

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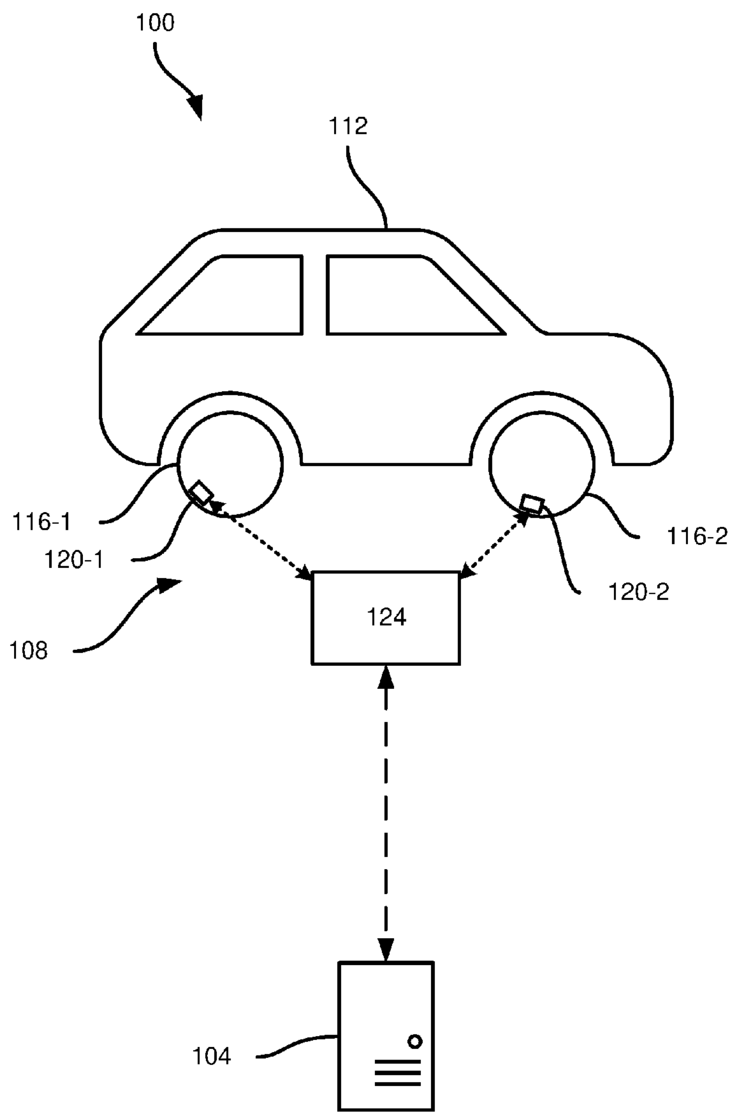
(57) **ABSTRACT**

An example sensing arrangement for a tire includes: a substrate configured to couple the sensing arrangement to an inner side of the tire; a deformation sensor supported by the substrate and configured to collect deformation data representing deformation at the inner side of the tire; a control module configured to transmit the deformation data collected by the deformation sensor to a recipient device.



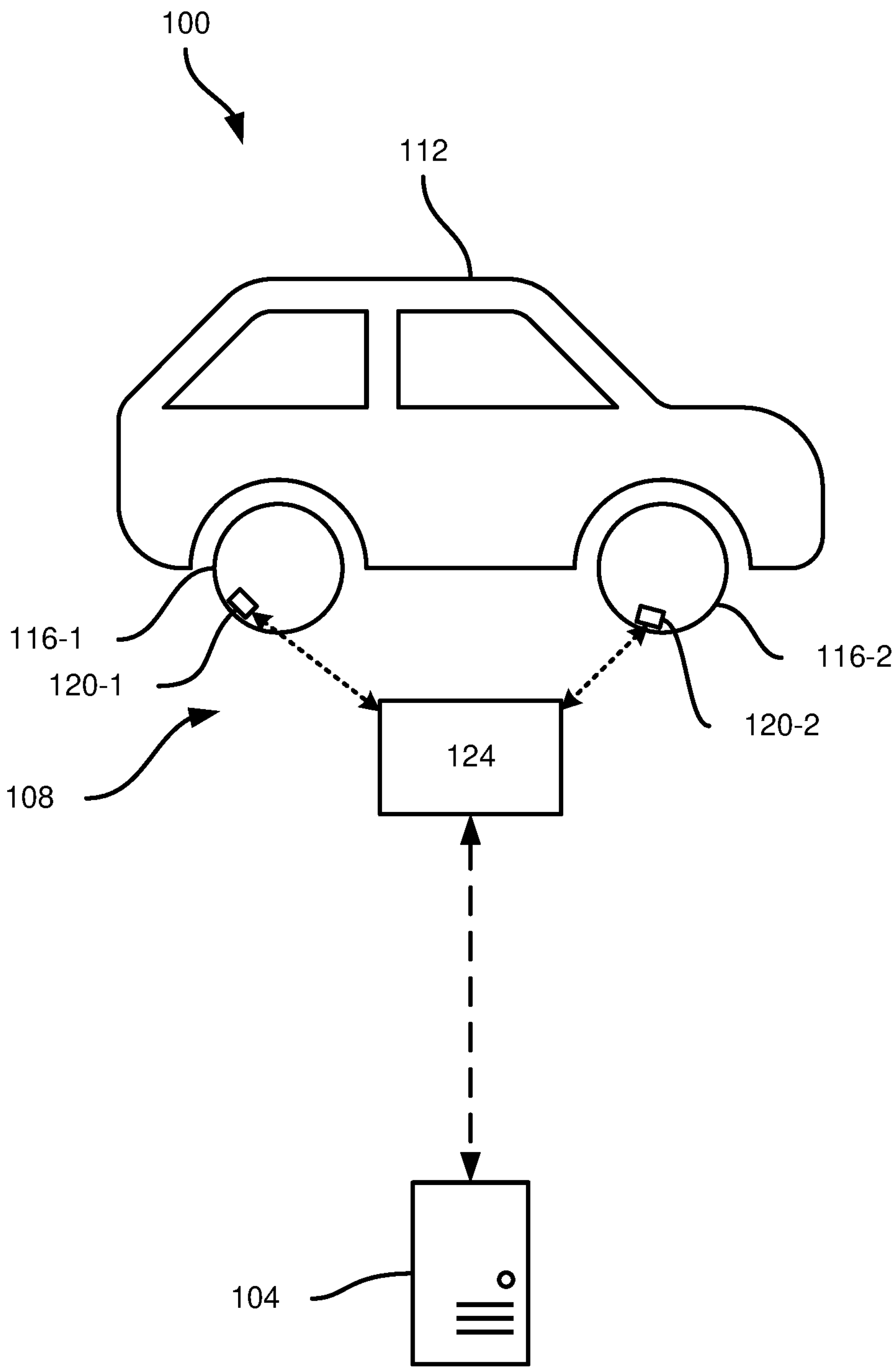


FIG. 1

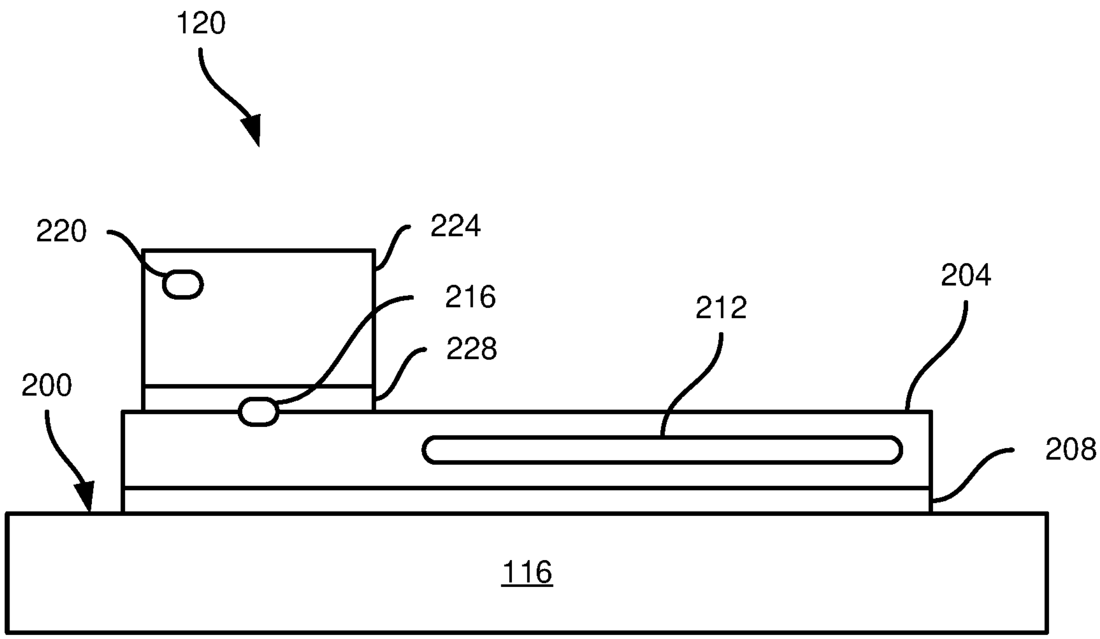

120
220
224
216
228
212
204
200
208
116

FIG. 2A

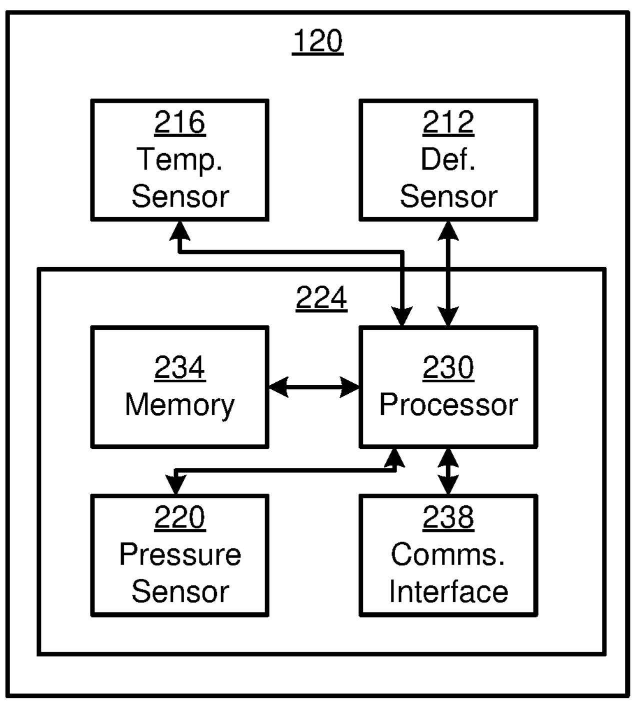

120
216
Temp.
Sensor
212
Def.
Sensor
224
234
Memory
230
Processor
220
Pressure
Sensor
238
Comms.
Interface

FIG. 2B

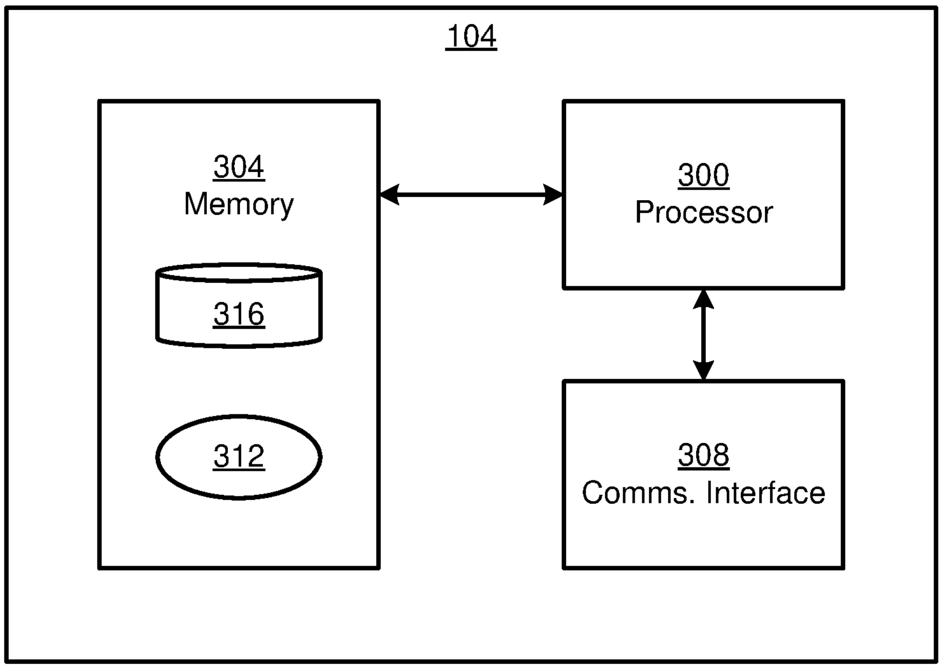


FIG. 3

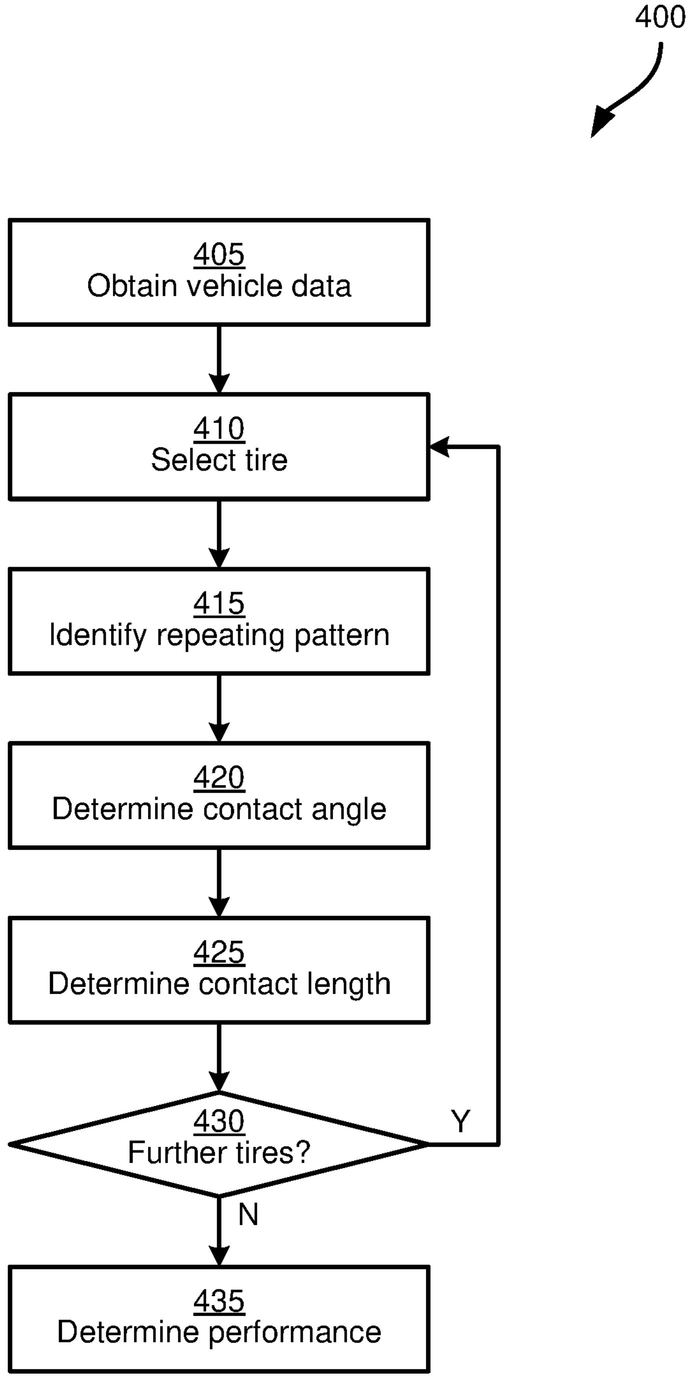

400
405
Obtain vehicle data
410
Select tire
415
Identify repeating pattern
420
Determine contact angle
425
Determine contact length
430
Further tires?
Y
N
435
Determine performance

FIG. 4

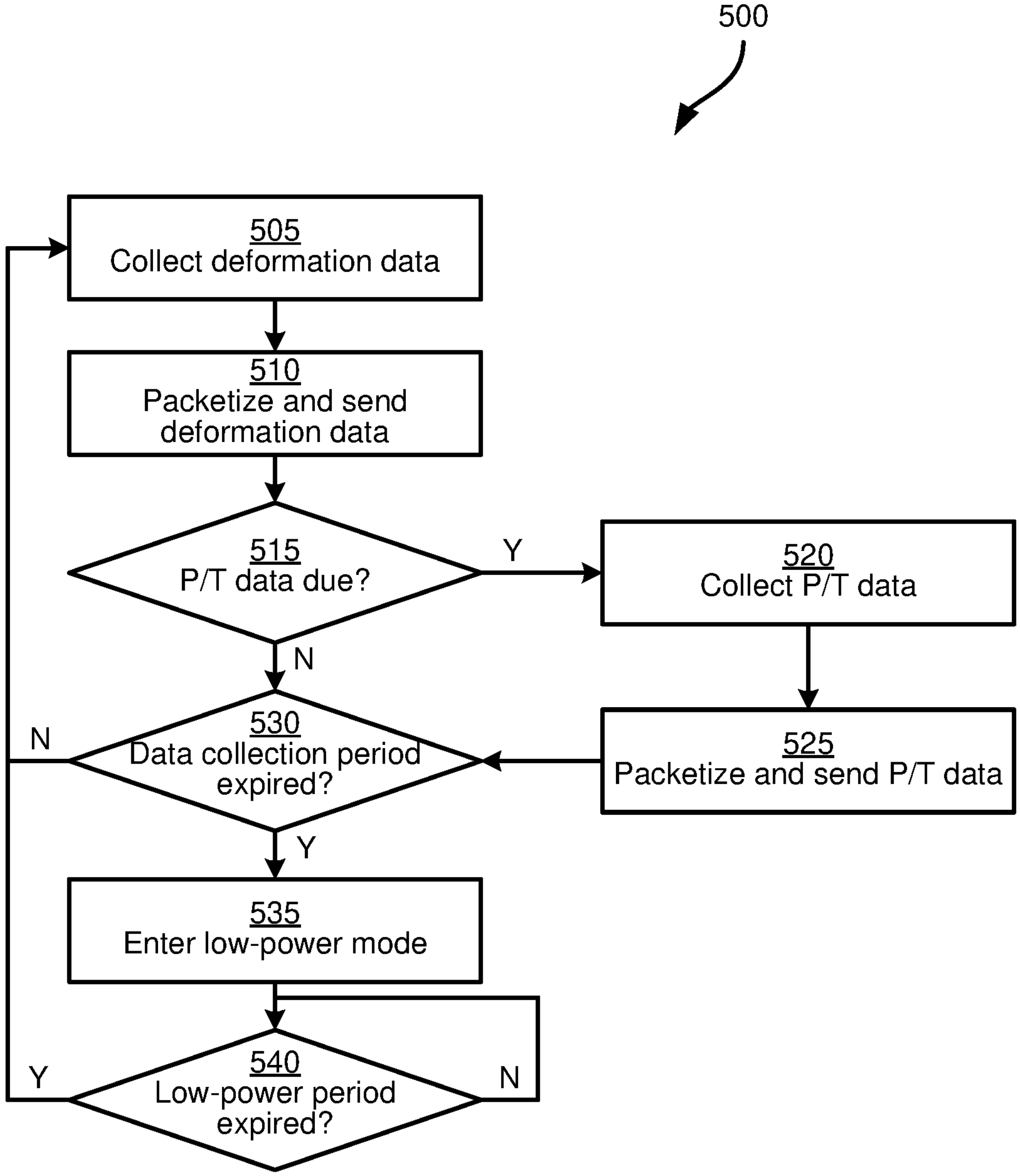

500
505
Collect deformation data
510
Packetize and send deformation data
515
P/T data due?
Y
520
Collect P/T data
N
530
Data collection period expired?
N
525
Packetize and send P/T data
Y
535
Enter low-power mode
540
Low-power period expired?
Y
N

FIG. 5

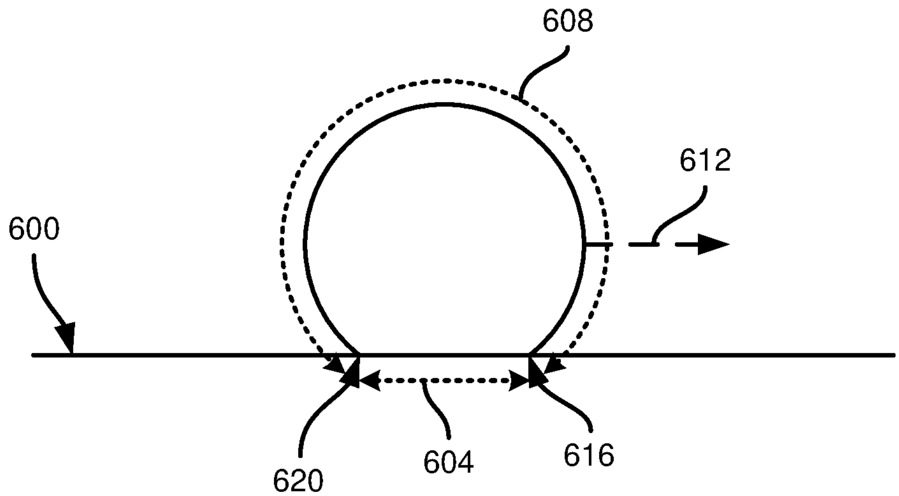


FIG. 6A

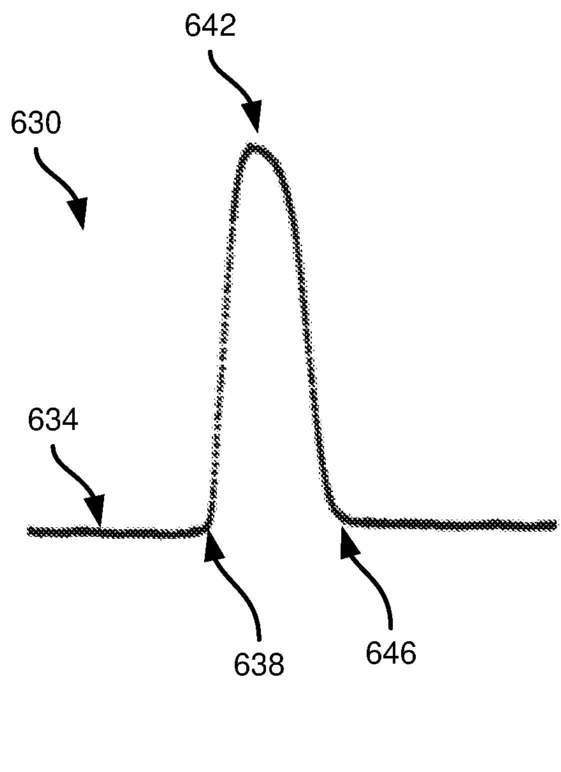


FIG. 6B

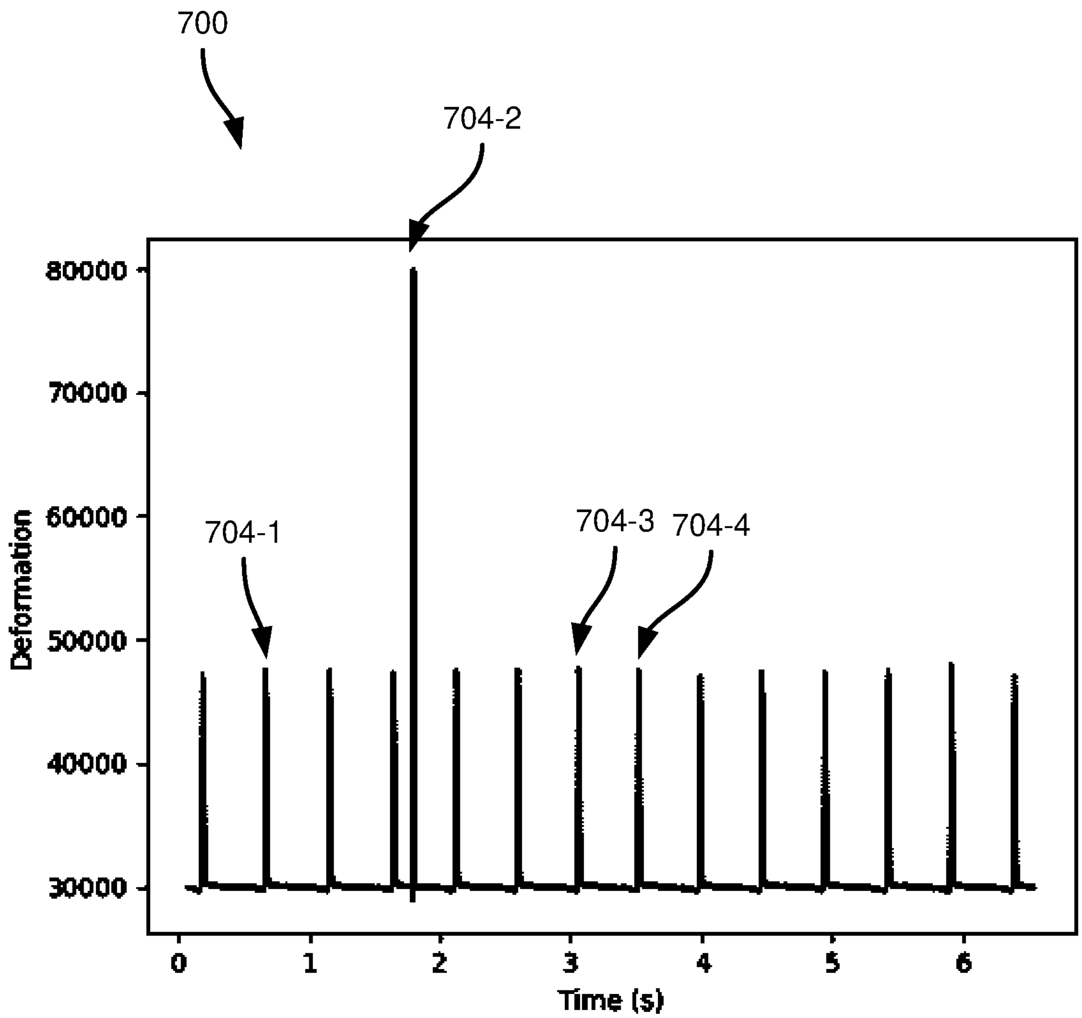

700
704-2
704-1
704-3
704-4
80000
70000
60000
50000
40000
30000
Deformation
0
1
2
3
4
5
6
Time (s)

FIG. 7

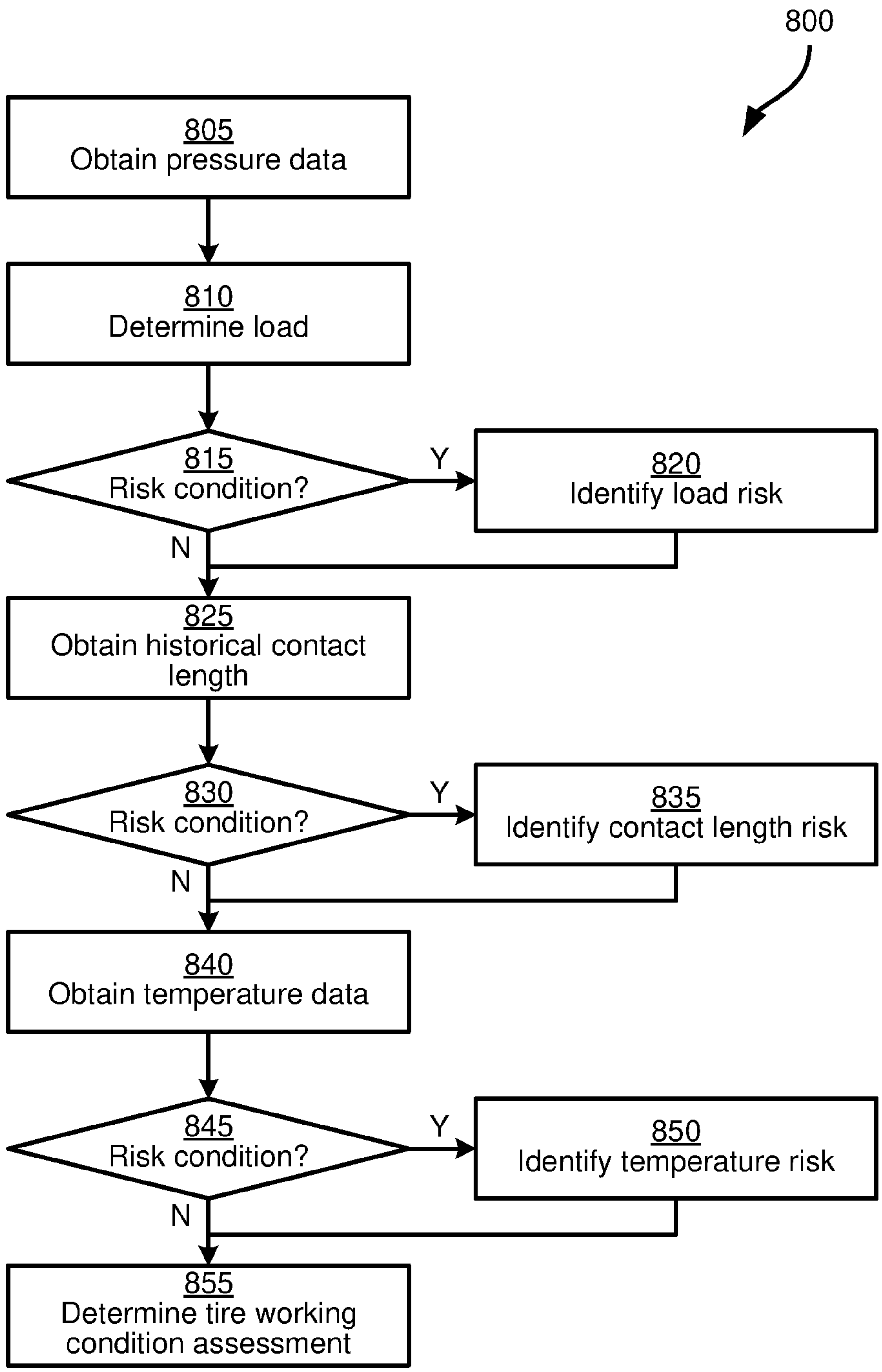

800
805
Obtain pressure data
810
Determine load
815
Risk condition?
Y
N
820
Identify load risk
825
Obtain historical contact length
830
Risk condition?
Y
N
835
Identify contact length risk
840
Obtain temperature data
845
Risk condition?
Y
N
850
Identify temperature risk
855
Determine tire working condition assessment

FIG. 8

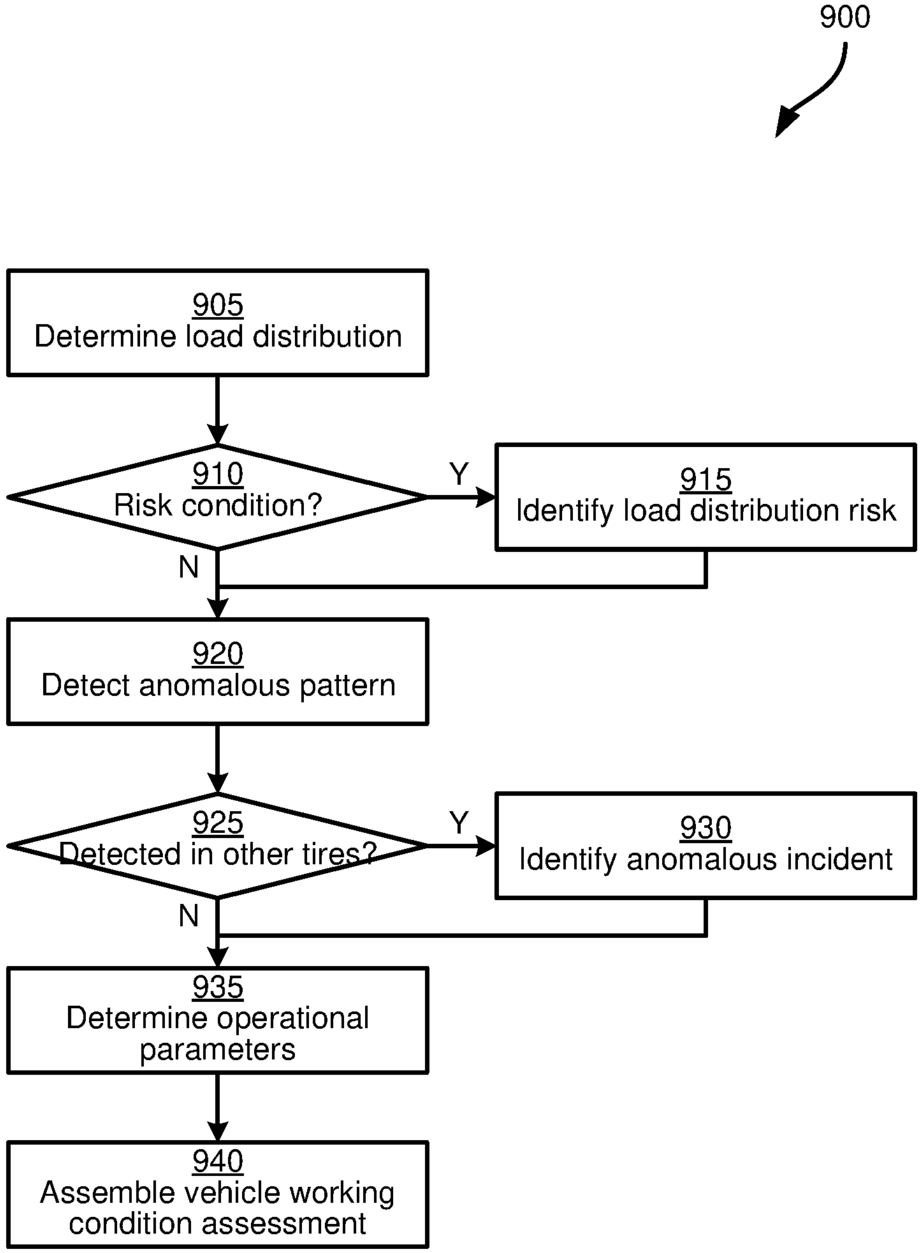

900
905
Determine load distribution
910
Risk condition?
Y
N
915
Identify load distribution risk
920
Detect anomalous pattern
925
Detected in other tires?
Y
N
930
Identify anomalous incident
935
Determine operational parameters
940
Assemble vehicle working condition assessment

FIG. 9

1000

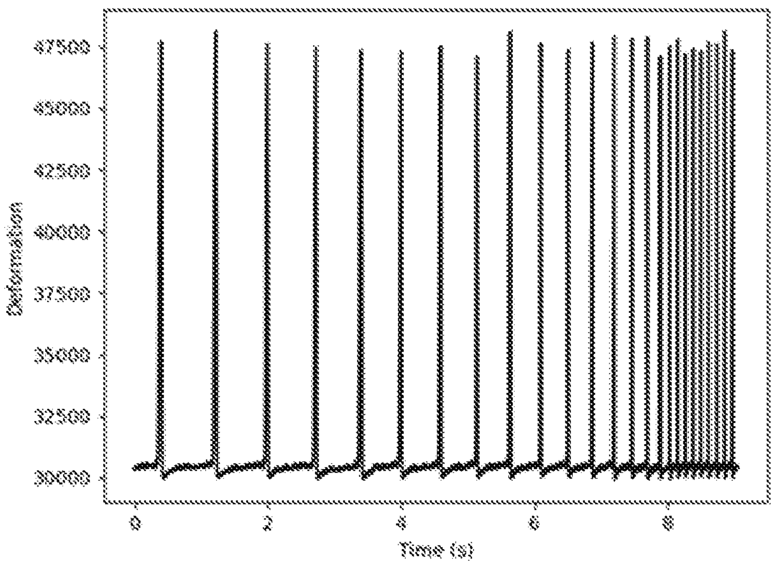


FIG. 10A

1010

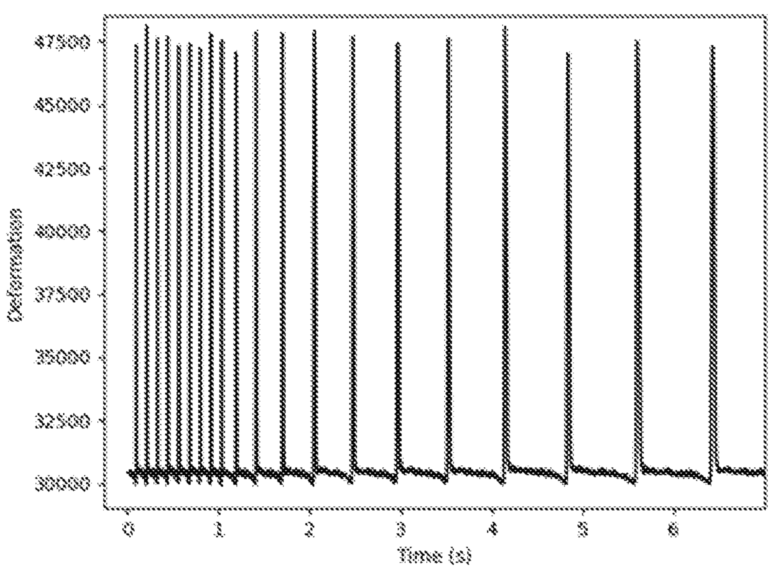


FIG. 10B

SYSTEM AND METHOD FOR MONITORING TIRES

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority from U.S. Application No. 63/330,920, filed on Apr. 14, 2022, the contents of which are incorporated herein by reference.

FIELD

[0002] The specification relates generally to vehicular monitoring systems, and more particularly to a system and method for monitoring tires on vehicles.

BACKGROUND

[0003] Tires can be found in many applications, particularly to transport people and goods in vehicles. Tracking tire performance can help increase safety and reduce the risk of overuse of worn tires. However, existing tire monitoring systems monitor a limited number of factors, which provides limited capability for tracking tire performance.

SUMMARY

[0004] According to an aspect of the present specification an example sensing arrangement for a tire includes: a substrate configured to couple the sensing arrangement to an inner side of the tire; a deformation sensor supported by the substrate and configured to collect deformation data representing deformation at the inner side of the tire; a control module configured to transmit the deformation data collected by the deformation sensor to a recipient device.

[0005] According to another aspect of the present specification, an example tire monitoring system includes: a set of sensing arrangements, each sensing arrangement configured to couple to an inner side of one of the tires in the set to collect deformation data representing deformation at the inner side of the tire; a monitoring hub configured to aggregate the deformation data from each sensing arrangement in the set and transmit the aggregated deformation data to a server.

[0006] According to another aspect of the present specification, an example server includes: a memory; a communications interface; and a processor interconnected with the memory and the communications interface, the processor configured to: obtain deformation data representing deformation of the tire over a series of rotations; detect a repeating pattern in the deformation data; determine, based on the repeating pattern, a contact angle of the tire; determine a contact length as a product of the contact angle and a radius of the tire; and determine a working condition assessment of the tire based on the contact length.

[0007] According to another aspect of the present specification, an example method includes: obtaining deformation data representing deformation of the tire over a series of rotations; detecting a repeating pattern in the deformation data; determining, based on the repeating pattern, a contact angle of the tire; determining a contact length as a product of the contact angle and a radius of the tire; and determining a working condition assessment of the tire based on the contact length.

BRIEF DESCRIPTION OF DRAWINGS

[0008] Implementations are described with reference to the following figures, in which:

[0009] FIG. **1** depicts a schematic diagram of an example tire monitoring system in accordance with the present disclosure.

[0010] FIG. **2**A depicts a schematic diagram of the sensing arrangement for monitoring tires of FIG. **1**.

[0011] FIG. **2**B depicts a block diagram of certain internal components of the sensing arrangement of FIG. **1**.

[0012] FIG. **3** depicts a block diagram of certain internal components of the server of FIG. **1**.

[0013] FIG. **4** depicts a flowchart of an example method of monitoring tires in accordance with the present disclosure.

[0014] FIG. **5** depicts a flowchart of an example method of obtaining vehicle data for block **405** of the method of FIG. **4**.

[0015] FIGS. **6**A and **6**B depict a schematic diagram of a tire in rotation and a corresponding deformation pulse, respectively.

[0016] FIG. **7** depicts a schematic diagram of example deformation data obtained in the tire monitoring system of FIG. **1**.

[0017] FIG. **8** depicts a flowchart of an example method of determining tire performance at block **435** of the method of FIG. **4**.

[0018] FIG. **9** depicts a flowchart of an example method of determining vehicle performance at block **435** of the method of FIG. **4**.

[0019] FIGS. **10**A and **10**B depict schematic diagrams of further example deformation data obtained in the tire monitoring system of FIG. **1**.

DETAILED DESCRIPTION

[0020] Typical tire monitoring systems often measure tire pressure and may sometimes additionally measure tire temperature. However, the pressure and temperature measurements typically occur at the valve stem, resulting in a temperature representative of the air cavity in the tire rather than the rubber material of the tire itself. Accordingly, such measurements are less valuable for predictive monitoring as the actual temperature of the tire, since the difference in temperature between the air cavity and the rubber material is inconsistent. Further, the pressure of the tire alone provides limited insights into tire performance. Another factor for monitoring tire performance is the length of the patch of tire which is in contact with the surface on which the tire is travelling, or the contact length. Typically, the contact length is a difficult factor to measure, and cannot be derived based on temperature and pressure measurements obtained in existing systems.

[0021] In accordance with the present disclosure, a system and method for determining tire performance includes obtaining deformation data representing the deformation of the tire over a series of rotations. The deformation data may be analyzed to detect a repeating pattern, determine a contact angle from the repeating pattern, and determine a contact length from the contact angle. The contact length may then be analyzed in context of the temperature and pressure to determine a working condition assessment of the tire.

[0022] Additionally, the configuration of the sensing arrangement used to obtain the deformation data allows for placement of the temperature sensor adjacent to the inner side of the tire, and the tire material itself, such that the temperature measurements obtained from the temperature sensor are representative of the tire itself, rather than the air cavity. Accordingly, the temperature data, pressure data and deformation data allow for a more robust assessment of the working conditions of the tire. Further, the tire data may be accumulated and correlated with data for other tires on the same vehicle to obtain vehicle data, as well as correlated to historical data to determine tire performance over time.

[0023] FIG. **1** depicts a system **100** for monitoring tires to determine tire performance and wear. The system **100** includes a server **104** interconnected with a tire monitoring system **108**. The tire monitoring system **108** is configured to monitor a vehicle **112**, and more particularly, a set of tires, of which two tires **116-1** and **116-2** (referred to generically as a tire **116** and collectively as tires **116** or the set of tires **116**; this nomenclature is used elsewhere herein), are shown. The vehicle **112** may be an automotive vehicle, such as a car, a truck, or the like, or may include other types of vehicles, such as a wagon, a trailer, a plane, a wheelbarrow, or other vehicle including load-bearing tires for monitoring the performance of said tires. Accordingly, the vehicle **112** may include four tires **116**, or more tires (e.g., eighteen tires on a semi-trailer truck) or fewer tires (e.g., one tire on a wheelbarrow) in other examples.

[0024] The server **104** is generally configured to analyze vehicle data including data representing the environmental conditions experienced by the tires **116**. The server **104** may use the vehicle data to determine tire performance, including detecting wear and potential issues with the tires, load balancing, and the like. The server **104** may be any suitable server environment, including a series of cooperating servers, one or more cloud-based servers, and the like. The internal components of the server **104** will be described in greater detail below.

[0025] The tire monitoring system **108** is generally configured to collect the vehicle data and transmit the vehicle data to the server. Specifically, the tire monitoring system **108** includes a set of sensing arrangements, of which two sensing arrangements **120-1** and **120-2** are depicted, and may further include a monitoring hub **124**.

[0026] Each of the sensing arrangements **120** is coupled to one of the tires **116** of the vehicle **112**. Preferably, the tire monitoring system **108** includes one sensing arrangement **120** per tire **116** of the vehicle **112**. Accordingly, if the vehicle **112** is a car having four tires **116** (of which only two are depicted), then the tire monitoring system **108** may also include four sensing arrangements **120** (of which only two are depicted). The sensing arrangements **120** are preferably coupled to an inner side of the tires **116** and are configured to measure tire data, including deformation data representing deformations experienced by the tires **116** (e.g., at portion of the tires **116** in contact with a surface on which the vehicle **112** is moving), temperature data representing the temperatures of the tires **116**, pressure data representing the air pressure within the tire cavities, and the like.

[0027] The sensing arrangements **120** may be in communication with the monitoring hub **124**. Preferably, the monitoring hub **124** may be local to the vehicle **112** to allow short-range wireless communications between the sensing arrangements **120** and the monitoring hub **124**. For example, the sensing arrangements **120** and the monitoring hub **124** may be in communication via a Bluetooth Low Energy (BLE) protocol or similar.

[0028] The monitoring hub **124** is generally configured to aggregate data from each of the sensing arrangements **120** to form vehicle data for the vehicle **112**. The monitoring hub **124** may therefore include a suitable processor or controller, a memory storing computer-readable instructions, and a communications interface to enable the functionality described herein. For example, the monitoring hub **124** may include a short-range wireless communications interface to communicate and receive tire data from the sensing arrangements **120**.

[0029] The monitoring hub **124** may further be in communication with the server **104** via one or more communication links, including wired and/or wireless communication links, combinations thereof, links which may traverse one or more networks, including local area networks, wide-area networks, the internet, and the like. Accordingly, the tire monitoring system **108** may be in communication with the server **104** via the monitoring hub **124** to send the vehicle data to the server **104**.

[0030] In some examples, the monitoring hub **124** may further include input and/or output devices, such as a display, speakers, a keyboard, a touch display, or the like, to allow an operator of the vehicle **112** to interact with the monitoring hub **124**. For example, the monitoring hub **124** may display the tire data collected by each of the sensing arrangements **120**, or analysis results from the server **104** based on the collected tire data, for example indicating the performance of each tire **116** (e.g., indicating that the tires **116** are in good operating condition or indicating detected risk and/or hazard conditions) and/or the vehicle performance. The monitoring hub **124** may further allow the operator of the vehicle **112** to connect one or more devices (e.g., a mobile device or the like) to allow the operator to receive updates on the determined performance.

[0031] Accordingly, in operation, each of the sensing arrangements **120** may collect tire data about conditions experienced by its respective tire **116** over a series of rotations. The tire data may include deformation data, temperature data, pressure, data, and the like. Each of the sensing arrangements **120** may send the tire data to the monitoring hub **124** over a short range wireless network. The monitoring hub **124** may aggregate the tire data of each of the tires **116** of the vehicle **112** to form vehicle data (e.g., associated with the vehicle **112**). The vehicle data, in turn, may be sent by the monitoring hub **124** to the server **104** for further analysis.

[0032] The server **104** may analyze the vehicle data captured by the sensor arrangements **120** to determine tire performance. For example, the server **104** may use the deformation data to determine a contact length for each tire **116**. The contact length, together with the pressure data, for example, may allow the server **104** to determine the load on each tire **116**. The server **104** may further correlate the load on each of the tires **116** of the vehicle **112** to determine the load distribution between the tires **116** of the vehicle **112**. The server **104** may aggregate the tire performance factors to determine a working condition assessment of each individual tire, as well as vehicle performance factors to determine a working condition assessment of the vehicle.

[0033] Turning now to FIG. **2**A, a schematic diagram of the sensing arrangement **120** according to an example. In particular, the sensing arrangement **120** is depicted as being coupled to one of the tires **116**, and more particularly, to an inner side **200** of the tire **116**. In particular, the tire **116** may be mounted on a rim (not shown) to define a cavity between the tire **116** and the rim. The cavity may be inflated with air to pressurize the tire **116** to allow the tire **116** to function to support the vehicle **112**. Accordingly, the sensing arrangement **120** may be applied within the cavity on the inner side **200** of the tire **116**. Preferably, the sensing arrangement **120** may be applied at a center line of the width of the tire **116**. As presently depicted, the tire **116** is substantially flat; it will be understood that the tire **116** may be curved, such that the inner side **200** is concave relative to a center of the tire **116**.

[0034] The sensing arrangement **120** includes a substrate **204** configured to support the components of the sensing arrangement **120** and to couple the sensing arrangement **120** to the inner side **200** of the tire **116**. The substrate **204** may preferably be flexible to conform to the curvature of the tire **116**.

[0035] The sensing arrangement **120**, and more particularly the substrate **204**, may further include an adhesive layer **208** configured to adhere the substrate **204** to the inner side **200** of the tire **116**. The adhesive layer **208** may be any suitable adhesive material, including pressure-sensitive adhesives, contact adhesives, and the like or other suitable manners of adhering the substrate **204** to the inner side **200** of the tire **116**, such as by suction cup, including micro-suction cups, and the like. The adhesive layer **208** may be selected based on its compatibility with the rubber or other material of the tire **116** and/or an inner layer of the tire **116** which forms the inner side **200**.

[0036] The sensing arrangement **120** further includes a set of sensors, including a deformation sensor **212**, a temperature sensor **216**, and a pressure sensor **220**. In other examples, the sensing arrangement **120** may include multiple deformation sensors **212**, multiple temperature sensors **216**, multiple pressure sensors **220**, other types of sensors or combinations of sensors, and the like.

[0037] The deformation sensor **212** is supported by the substrate **204**, and in the present example, is embedded within the substrate **204**, for example to protect the deformation sensor **212** from damage during installation of the sensor arrangement **120**. The deformation sensor **212** is generally configured to detect deformation over the length of the deformation sensor **212**. Accordingly, when the sensor arrangement **120** is installed on the inner side **200** of the tire **116**, the deformation sensor **212** detects deformation at the inner side **200** of the tire **116**. Preferably, the deformation sensor **212** may have a length exceeding a length of a tread pattern of the tire. That is, the deformation sensor **212** is preferably sized such that deformations detected over the length of the deformation sensor **212** pertain to the tire **116** rather than being affected more local deformations due to tread movements.

[0038] For example, the deformation sensor **212** may be a strain sensor configured to measure strain at the inner side **200** of the tire **116**. The strain sensor may include, for example, nanomaterial-coated fibers or a yarn of nanomaterial-coated fibers as described in U.S. patent application Ser. No. 16/977,711, the contents of which are incorporated herein by reference. In other examples, the deformation sensor **212** may be a force sensor, a pressure sensor, or another sensor configured to monitor a change in curvature of the tire **116** as the deformation sensor **212** passes through the contact length of the tire **116** as further described below.

[0039] The temperature sensor **216** is supported by the substrate **204** adjacent to the inner side **200** of the tire **116**. That is, the temperature sensor **216** may be supported by the substrate **204** within a threshold distance of the inner side **200** of the tire **116**. The threshold distance may be selected according to an operational range of the temperature sensor **216**. Thus, the temperature sensor **216** may be supported by the substrate **204** at a distance from the inner side **200** of the tire **116** which is within its operational range, to allow the temperature sensor **216** to detect the temperature of the inner side **200** of the tire **116**. Accordingly, the temperature sensor **216** is configured to measure the temperature of the tire **116** itself, rather than the temperature of the air cavity within the tire **116**.

[0040] Thus, in the present example, the temperature sensor **216** is at least partially embedded in the substrate **204** to position the temperature sensor **216** adjacent to the inner side **200** of the tire **116** when the sensing arrangement **120** is installed on the tire **116**.

[0041] The sensing arrangement **120** further includes a pressure sensor **220** supported by the substrate **204** and generally configured to detect an air pressure of the air cavity within the tire **116**. That is, the pressure sensor **220** determines an internal tire pressure for the tire **116**. Accordingly, the pressure sensor **220** may be supported by the substrate **204** away from the inner side **200** of the tire **116** to position the pressure sensor **220** closer to a center of the air cavity of the tire **116**.

[0042] The sensing arrangement **120** further includes an electronics module **224**. In the present example, the pressure sensor **220** is embedded within the electronics module **224**, for example on a printed circuit board within the electronics module **224**. The electronics module **224** is generally configured to manage raw data collected by the set of sensors and to communicate the raw data to a recipient device. In some examples, the electronics module **224** may further be configured to filter data, perform calculations, and the like to control and reduce the amount of data communicated to the recipient device.

[0043] The electronics module **224** may preferably include a housing, such as an enclosure, in which the electronics of the sensing arrangement **120** are housed, to protect the electronics. Preferably, the electronics module **224** may be supported on the substrate **204** and set away from the substrate **204** by a vibration damping portion **228**. The vibration damping portion **228** may be a flexible material (e.g., rubber or the like) to dampen transmission of vibrations or other shocks experienced by the tire **116** to the electronics module **224**. In some examples, the vibration damping portion **228** may support the entirety of the electronics module **224**, including the housing and the electronics housed therein, away from the inner side **200** of the tire **116**, while in other examples, the vibration damping portion **228** may be enclosed in the housing of the electronics module **224** to isolate the electronic components within the electronics module **224** from vibrations experienced by the substrate **204** and transmitted through the housing.

[0044] FIG. 2B depicts a block diagram of certain internal components of the sensing arrangement **120**, and in particular, of the electronics module **224**. The electronics module **224** may house a processor **230**, interconnected with a memory **234** and a communications interface **238**.

[0045] The processor **230** may include a microcontroller, a microprocessor, a processing core, a field-programmable gate array (FPGA), an application-specific integrated circuit

(ASIC), or other suitable control unit capable of executing instructions. The processor **300** may include multiple cooperating processors.

[0046] The memory **234** may include a combination of volatile (e.g., Random Access Memory or RAM) and non-volatile memory (e.g., read-only memory or ROM, Electrically Erasable Programmable Read Only Memory or EEPROM, flash memory). All or some of the memory **234** may be integrated with the processor **230**. The memory **234** may store computer readable instructions which when executed, configure the sensing arrangement **120** to perform the functionality described herein.

[0047] The communications interface **238** may be configured for wireless (e.g., Bluetooth, Wi-Fi, or other suitable communications protocols) communications and may include suitable hardware (e.g., transmitters, receivers, network interface controllers, and the like) to allow the sensing arrangement **120** to communicate with other computing devices, such as the monitoring hub **124**. Accordingly, the communications interface **238** may preferably be configured for short range wireless communications. In other examples, the sensing arrangements **120** may communicate with the server **104** directly, and hence may be configured for long range wireless communications. For example, the communications interface **238** may be configured for low power, wide area network communications.

[0048] The processor **230** is interconnected with the memory **234** and the communications interface **238**, as well as with each of the sensors in the sensor suite, including the deformation sensor **212**, the temperature sensor **216** and the pressure sensor **220**. That is, the processor **230** may, in some examples, control the data collection operation by each of the sensors **212**, **216**, and **220**, as well as obtaining and processing the data collected by each of the sensors **212**, **216**, and **220**.

[0049] Turning now to FIG. **3**, certain internal components of the server **104** are depicted in greater detail. The server **104** includes a processor **300**, a memory **304** and a communications interface **308**.

[0050] The processor **300** may include a central processing unit (CPU), a microcontroller, a microprocessor, a processing core, a field-programmable gate array (FPGA), or similar. The processor **300** may include multiple cooperating processors. The processor **300** may cooperate with the memory **304** to realize the functionality described herein.

[0051] The memory **304** may include a combination of volatile (e.g., Random Access Memory or RAM) and non-volatile memory (e.g., read-only memory or ROM, Electrically Erasable Programmable Read Only Memory or EEPROM, flash memory). All or some of the memory **304** may be integrated with the processor **300**. The memory stores applications, each including a plurality of computer-readable instructions executable by the processor **300**. The execution of the instructions by the processor **300** configures the server **104** to perform the actions discussed herein. In particular, the applications stored in the memory **304** include a tire monitoring application **312**. When executed by the processor **300**, the application **312** configures the processor **300** to perform various functions discussed below in greater detail and related to the tire monitoring operation of the server **104**. The application **312** may also be implemented as a suite of distinct applications. Further, Some or all of the functionality of the application **312** may be implemented as dedicated hardware components, such as one or more FPGAs or application-specific integrated circuits (ASICs).

[0052] The memory **304** also stores a repository **316** storing rules and data for the tire monitoring operation. For example, the repository **316** may store associations between tires **116** and vehicles **112**, associations between vehicles **112**, user accounts (e.g., to subscribe to performance analysis results) and user devices (e.g., to provision analysis results to the user), historical data for each of the tires **116** and each of the vehicles **112**, and the like.

[0053] The server **104** further includes the communications interface **308** interconnected with the processor **300**. The communications interface **308** may be configured for wireless (e.g., satellite, radio frequency, Bluetooth, Wi-Fi, or other suitable communications protocols) or wired communications and may include suitable hardware (e.g., transmitters, receivers, network interface controllers, and the like) to allow the server **104** to communicate with other computing devices. The specific components of the communications interface **308** are selected based on the types of communication links that the server **104** communicates over.

[0054] The server **104** may further include one or more input and/or output devices (not shown). The input devices may include one or more buttons, keypads, touch-sensitive display screen, mice, or the like for receiving input from an operator. The output devices may include one or more display screens, monitors, speakers, sound generators, vibrators, or the like for providing output or feedback to an operator.

[0055] Turning now to FIG. **4**, the functionality implemented by the server **104** will be discussed in greater detail. FIG. **4** illustrates a method **400** of monitoring tires. The method **400** will be discussed in conjunction with its performance in the system **100** and in particular by the server **104** via execution of the application **312**. In particular, the method **400** will be described with reference to the components of FIGS. **1** to **3**. In other examples, the method **400** may be performed, in whole or in part, by other suitable devices or systems, such as the monitoring hub **124**, or the processor **230** of the sensing arrangement **120**.

[0056] At block **405**, the server **104** obtains vehicle data data, including tire data corresponding to each of the tires **116** of the vehicle **112**. The tire data corresponding to each of the tires **116** may include deformation data representing deformation of the tire **116** over a series of rotations of the tire **116**. In some examples, the tire data may further include temperature data and pressure data for the tire **116**.

[0057] The tire data for each tire **116** may be collected at the tire **116** by the corresponding sensing arrangement **120** coupled to the tire. Accordingly, the deformation data may be collected at the tire **116** by the deformation sensor **212** located at the inner side **200** of the tire **116**. In particular, the deformation sensor **212** may be a strain sensor configured to measure strain at the inner side **200** of the tire **116**. The temperature data may be collected by the temperature sensor **216** located at the inner side **200** of the tire **116** and in particular, located adjacent to the inner side **200** of the tire **116** to measure the temperature of the tire **116** itself rather than the air cavity of the tire. Further, the pressure data may be collected by the pressure sensor **220**.

[0058] For example, referring to FIG. **5**, an example method **500** of collecting tire data is depicted. The method **500** may be performed, for example, by the sensing arrangement **120**, or other suitable devices and/or systems.

[0059] At block **505**, the sensing arrangement **120**, and more particularly, the deformation sensor **212**, collects deformation data. For example, the deformation sensor **212** may be a strain sensor which measures electrical resistance through the strain sensor to determine strain. That is, the electrical resistance measurements may vary according to (e.g., proportionally or inversely proportionally) to the strain experienced by the strain sensor.

[0060] For example, FIG. **6**A depicts an example schematic diagram of the tire **116** supported on a surface **600**. On the surface **600**, the tire **116** deforms along a contact length **604** to conform to the surface **600**, with a free length **608** is disposed away from the surface **600**. As the tire **116** rotates on the surface **600**, for example moving in a direction **612**, the deformation sensor **212** effectively rotates in a clockwise direction along the perimeter of the tire **116**.

[0061] Accordingly, when the deformation sensor **212** is disposed along the free length **608**, the tire **116** is in its neutral shape, and hence the deformation sensor **212** may detect a baseline level of deformation. When the deformation sensor **212** is disposed at an entry point **616** of the contact length **604**, the local region of the tire **116** about the deformation sensor **212** shifts from its neutral shape to a deformed shape to accommodate the surface **600**. Accordingly, at the entry point **616**, the deformation sensor **212** detects a first deformation shift. As the deformation sensor **212** moves along the contact length **604**, the local region of the tire **116** about the deformation sensor **212** may deform further to continue accommodating the surface **600**. Accordingly, the deformation sensor **212** may detect a deformation peak over the contact length **604**. When the deformation sensor **212** is disposed at an exit point **620** of the contact length **604**, the local region of the tire **116** about the deformation sensor **212** shifts from the deformed shape back to its neutral shape upon moving away from the surface **600**. Accordingly, the deformation sensor **212** may detect a second deformation shift at the exit point **620**.

[0062] Thus, for example, referring to FIG. **6**B, an example pulse **630** defined by the deformation data is depicted. Specifically, the pulse **630** depicts strain experienced by the tire **116** over the course of a single rotation. The tire **116** experiences a uniform strain while the tire **116** is in its neutral shape and curvature over the free length **608**, forming a baseline **634** of the pulse **630**. As the deformation sensor **212** moves to the entry point **616**, the curvature of the local region of the tire **116** about the deformation sensor **212** increases, thereby decreasing the strain. Accordingly, the pulse **630** may exhibit a first deformation shift **638** (e.g., a decrease in strain) when the location of the deformation sensor **212** corresponds to the entry point **616**. As the deformation sensor **212** moves along the contact length **604**, the curvature of the local region of the tire **116** about the deformation sensor **212** decreases, thereby increasing the strain. Accordingly, the pulse **630** may exhibit a deformation peak **642** over the contact length **604**. Finally, as the deformation sensor **212** moves to the exit point **620**, the curvature of the local region of the tire **116** about the deformation sensor **212** again increases, thereby decreasing the strain. Accordingly, the pulse **630** may exhibit a second deformation shift **646** (e.g., a decrease in strain) when the location of the deformation sensor **212** corresponds to the exit point **620**.

[0063] Preferably, to accurately detect the first and second deformation shifts **638** and **646**, as well as the deformation peak **642**, the deformation sensor **212** may collect at least ten data points over the deformation peak. Accordingly, based on typical car tire speeds and contact angles (i.e., the angle which subtends the contact length **604**), the deformation sensor **212** may preferably collect measurements at a frequency of at least about 3600 Hz. According to an example, the deformation sensor **212** may implement a roughly 4200 Hz measurement frequency. In other examples, the measurement frequency may be higher, for example for higher speed applications.

[0064] Returning to FIG. **5**, at block **510**, the sensing arrangement **120** packetizes deformation data. That is, in order to send the data to a recipient device, the deformation data collected at block **505** may be condensed by reducing each measurement to a 2-byte value. Further, since the deformation sensor **212** is configured to collect data at a constant frequency, only two timestamps may be reported in the packetized data (e.g., one corresponding to an initial resistance or deformation measurement and one corresponding to a final resistance or deformation measurement). In some examples, the sensing arrangement **120** may perform further filtering operations and/or other types of data compression and the like prior to sending the data to the recipient device.

[0065] After condensing and packetizing the deformation data, the sensing arrangement **120** sends the data packet to a recipient device. According to a preferred example, the recipient device is the monitoring hub **124**, to allow the sensing arrangement **120** to employ a short-range, low energy communications protocol, such as BLE.

[0066] At block **515**, the sensing arrangement **120** determines whether pressure and/or temperature data measurement is due. In particular, since pressure and temperature do not change on the same timescales associated with the rotation frequency of a tire, the sensing arrangement **120** may track a separate timer for sending pressure and temperature data at an appropriate predefined frequency (e.g., once per second, 3 seconds, etc.).

[0067] If, at block **515**, the determination is affirmative, that is, that temperature and pressure are due to be collected, then the sensing arrangement **120** proceeds to block **520**. At block **520**, the sensing arrangement **120**, and more particularly, the temperature sensor **216** and the pressure sensor **220**, collect temperature and pressure measurements, respectively.

[0068] In particular, the temperature sensor **216** detects the temperature within its operational radius, and hence may particularly detect the temperature of the inner side **200** of the tire **116**. That is, the temperature measurements collected by the temperature sensor **216** may more closely correspond to temperatures experienced by the tire **116** itself, rather than temperatures generated within the air cavity of the tire **116**. The pressure sensor **220**, on the other hand, may detect the air pressure of the air cavity of the tire **116**.

[0069] At block **525**, the sensing arrangement **120** packetizes the temperature and pressure data. For example, the temperature and pressure measurements may similarly be reduced to a 2-byte value. In some examples, the packet containing temperature and pressure measurements may further include a battery voltage measurement to allow the battery state to be monitored. Further, in some examples, the packet containing temperature and pressure measurements may be combined with deformation data resistance measurements. In other examples, the packet may contain only temperature and pressure data, and the packet may be inserted into the queue to be sent amongst the deformation data packets. In some examples, the sensing arrangement **120** may perform further filtering operations and/or other types of data compression and the like prior to sending the data to the recipient device.

[0070] After condensing and packetizing the temperature and pressure data, the sensing arrangement **120** sends the data packet to the recipient device.

[0071] After sending the packetized temperature and pressure data at block **525**, or if no temperature and pressure measurements are due to be acquired (i.e., a negative determination at block **515**), the sensing arrangement **120** proceeds to block **530**. At block **530**, the sensing arrangement **120** determines if a data collection period has expired.

[0072] In order to achieve power efficient operation, the sensing arrangement **120** may operate intermittently. That is, the sensing arrangement **120** may operate in a low-power state for a predefined low-power period and may operate in a data collection mode for a predefined data collection period. In the low-power state, the sensing arrangement **120** may be in a "sleep" state, in which it is not measuring tire data or transmitting data. In the data collection mode, the sensing arrangement **120** may operate to collect tire data and transmit said data, in accordance with blocks **505** to **525** described above. For example, the predefined low-power period may be about 60 seconds, and the data collection period may be about 7 seconds. In other examples, the length of the low-power period and the data collection period may be adjusted to optimize battery life and to acquire sufficient data for analysis.

[0073] Accordingly, the sensing arrangement **120** may track the data collection period and check, at block **530**, whether the data collection period has expired. If the data collection period has not yet expired, the sensing arrangement **120** returns to block **505** to continue collecting further deformation data.

[0074] If, at block **530**, the data collection period has expired, the sensing arrangement **120** proceeds to block **535**. At block **535**, the sensing arrangement **120** enters the low-power or sleep state to reduce energy and battery consumption. The sensing arrangement **120** may further initiate a timer to track the low-power period and reset a timer tracking the data collection period.

[0075] At block **540**, the sensing arrangement **120** determines whether the low-power period has expired. If the low-power period has not expired, the sensing arrangement **120** is maintained in its low-power state.

[0076] If the low-power period has expired, then the sensing arrangement **120** transitions to the data collection mode and returns to block **505** to collect deformation data. Upon moving to the data collection mode, the sensing arrangement **120** may reset the timer for the low-power period and initiate a timer to track the data collection period.

[0077] Accordingly, the sensing arrangement **120** may regularly send deformation data, as well as temperature and pressure data, to a recipient device. In the present example, the recipient device is the monitoring hub **124**. The monitoring hub **124** may therefore receive tire data from each of the sensing arrangements **120** corresponding to each of the tires **116** of the vehicle **112**.

[0078] The monitoring hub **124** may aggregate the tire data from each of the tires **116** to form vehicle data for the vehicle **112**. For example, the monitoring hub **124** may correlate each set of tire data with a vehicle identifier or the like. Correlation of the tire data experienced by each of the tires **116** of the vehicle **112** may allow subsequent analysis of overall vehicle performance and suggestions to improve vehicle performance, for example based on load distribution, and the like. Further, in some examples, the monitoring hub **124** may correlate each set of tire data with a trip identifier, for example to identify separate trips which the vehicle **112** makes (i.e., where each trip may be distinguished by an extended period in which the vehicle **112** and the tires **116** are stationary).

[0079] In some examples, the analysis of performances of the vehicle **112** and the tires **116** may be performed by the monitoring hub **124** itself, based on the tire data from each of the tires **116**. In other examples, the monitoring hub **124** may aggregate the tire data and transmit the tire data to the server **104**. In still further examples, the sensing arrangement **120** may bypass the monitoring hub **124** and send the tire data directly to the server **104** as the recipient device.

[0080] Returning to FIG. **4**, at block **410**, after obtaining the deformation data, and temperature data and pressure data as applicable, the server **104** selects one of the tires **116** to analyze. In particular, as the vehicle **112** and the tires **116** rotate to move the vehicle **112**, the server **104** may expect that each given tire **116** undergoes substantially equal forces on each rotation, and hence the deformation experienced by the tire **116** in any given rotation may be substantially equal to the deformation experienced in any other rotation. Accordingly, each rotation of the tire **116** may generate substantially the same pattern in the deformation data. Accordingly, the server **104** may select one of the tires **116**, extract the corresponding deformation data from the vehicle data, and analyze the deformation data for the selected tire **116**.

[0081] At block **415**, the server **104** identifies a repeating pattern in the deformation data for the tire selected at block **410**. For example, the deformation data may include a series of deformation pulses, such as the pulse **630** depicted in FIG. **6**B, each corresponding to a rotation of the tire **116** as the vehicle **112** travels on a surface.

[0082] For example, since the tires **116** may experience substantially the same deformation over a given rotation, the server **104** may detect the repeating pattern based on similarity of portions of the deformation data to a representative model pattern (e.g., based on computer-simulated or ideal conditions).

[0083] In other examples, the server **104** may first identify the baseline for the deformation data (i.e., corresponding to the deformation and/or strain experienced by the tire **116** over its free length **604**. The server **104** may then detect deformation pulses, for example by identifying peaks (e.g., local maxima) in the deformation data. The server **104** may additionally verify that the identified pulses correspond to the repeating pattern, for example, based on a magnitude of the pulse being at least a certain threshold, within a threshold percentage or standard deviation of the average magnitude of other identified pulses, or similar. In other examples, other manners of detecting the repeating pattern are also contemplated.

[0084] For example, referring to FIG. **7**, example deformation data **700** is depicted. The deformation data **700** includes a series of deformation pulses, including pulses **704-1**, **704-2**, **704-3**, and **704-4**. Upon analysis, the server **104** may identify the pulses **704-1**, **704-3**, and **704-4** as forming a repeating pattern, for example, as having a magnitude within a threshold similarity as one another, and/or as having similar proportions. In contrast, the server **104** may determine that the pulse **704-2** is not part of the repeating pattern based in its magnitude.

[0085] Returning to FIG. **4**, at block **420**, the server **104** uses the repeating pattern to determine a contact angle of the tire **116**. The contact angle for the tire **116** is the angle which subtends the contact length of the tire **116**. For example, referring again to FIG. **5**, the contact angle for the tire **116** is given by the angle α. The contact angle α may be computed according to Equation (1):

$$\alpha = 2\pi \cdot t_c / t_r \tag{1}$$

[0086] In Equation (1), t_c represents the contact time for the deformation sensor **212**—that is, t_c represents the time for the sensor **212** to pass through the contact length **604** during a rotation—and t_r represents the revolution time for the deformation sensor **212** to complete a full revolution about the center of the tire **116**—that is, the time for the tire **116** to complete a full rotation.

[0087] Accordingly, the server **104** may analyze the deformation data to determine the contact time t_c and the revolution time t_r for the deformation sensor **212**. In particular, with reference to FIGS. **6**A and **6**B, the time at which the deformation sensor **212** enters the contact length **604** at the entry point **616** corresponds to the first deformation shift **638**, and the time at which the deformation sensor **212** exits the contact length **604** at the exit point **620** corresponds to the second deformation shift **646**. Accordingly, the contact time t_c may be computed based on the width of the deformation peak **642** of the pulse **630**.

[0088] For example, the width of the deformation peak **642** may be determined based on a full-width-half-maximum (i.e., compute the width between the two points corresponding to half the maximum height of the deformation peak **642**). In other examples, the width of the deformation peak **642** may be determined by identifying inflection points in the pulse **630** (i.e., the first and second deformation shifts **638** and **646**), based on a rise above a predefined threshold, by integrating under the deformation peak **642**, or other suitable methods.

[0089] The revolution time t_r corresponds to the time for the deformation sensor **212** to revolve from a given position, about the center of the tire **116**, and return to the same position. Since the position of the deformation sensor **212** along the free length **608** may produce approximately equivalent deformation values in the deformation data, the server **104** may use a position along the contact length **604** to track sequential equivalent positions of the deformation sensor **212**. For example, the server **104** may identify sequential instances of the first deformation shift **638** to detect sequential instances of the deformation sensor **212** at the entry point **616**. At a constant rotation (i.e., between sequential pulses **630**), the distance between sequential instances the first deformation shift **638** may be substantially equivalent to the distance between sequential instances of the deformation peak **642**. Accordingly, the server **104** may approximate the revolution time t_r based on the distance between sequential peaks.

[0090] For example, referring to FIG. **7**, the pulses **704-3** and **704-4** are sequential, and hence the server **104** may identify the deformation peaks of each of the pulses **704-3** and **704-4** (e.g., by identifying a global or local maximum in the respective pulse **704**) and use the distance between each of the detected deformation peaks as the revolution time t_r.

[0091] After determining both the contact time and the revolution time, the server **104** applies Equation (1) to obtain the contact angle α, provided in radians. In some examples, the server **104** may determine the contact angle for a single deformation pulse, for example selected as being representative of a subset of the deformation data (e.g., corresponding to a predefined time period). In other examples, the server **104** may determine the contact angle for a series of deformation pulses, for example selected as being representative of a subset of the deformation data, or for each deformation pulse in the deformation data. The server **104** may then filter outliers from the determined contact angles and compute an average contact angle.

[0092] Returning again to FIG. **4**, at block **425**, after determining the contact angle of the tire **116**, the server **104** determines the contact length for the tire. In particular, the server **104** may determine the contact length as a product of the contact angle α, determined at block **420**, and a radius of the tire **116**, according to Equation (2):

$$l_c = \alpha \cdot R \tag{2}$$

[0093] In Equation (2), l_c is the contact length of the tire **116**, and R is the radius of the tire **116**. The radius R may be a predetermined value, stored in the memory **304** of the server **104**, or in a memory of the monitoring hub **124** and transmitted to the server **104** with the vehicle data at block **405**.

[0094] Based on the contact angle(s) determined at block **420**, the server **104** may determine a single, representative contact length for the tire **116** (i.e., over a predefined period), a set of contact lengths for the tire **116**—which the server **104** may subsequently average to determine an average contact length for the tire **116**, e.g., over a predefined period, a contact length for the tire **116** which is based on the average contact angle for the tire **116**, or similar.

[0095] At block **430**, after determining the contact length for the tire **116** selected at block **410**, the server **104** determines whether the vehicle includes further tires **116** for which to determine the contact length. If the determination is affirmative, then the server **104** returns to block **410** to select a further tire **116** for the vehicle **112**.

[0096] If the determination at block **430** is negative, that is, the server **104** has determined the contact lengths for each of the tires **116** of the vehicle **112**, then the server **104** may proceed to block **435**.

[0097] At block **435**, the server **104** uses the vehicle data obtained at block **405** and the contact lengths determined at block **425** to evaluate tire performance for each of the tires **116** of the vehicle **112**, as well as vehicle performance of the vehicle **112** as a whole. That is, the server **104** may perform an analysis and determine a status and/or performance of each of the tires **116** individually. The server **104** may further perform an analysis and determine a status and/or performance of the tires **116** collectively, and in relation to one another. The tire and vehicle performances may result in a determination that the tires **116** and/or vehicle **112** are in good operating condition, or an identification of one or more hazard and/or risk conditions which may be communicated, for example, to an operator of the vehicle **112**.

[0098] For example, referring to FIG. **8**, a flowchart of an example method **800** of determining tire performance for a single tire **116** is depicted. In some examples, the operations of the method **800** may be performed in an order other than that depicted, and hence are referred to as blocks rather than steps.

[0099] At block **805**, the server **104** obtains pressure data for the tire **116**. The pressure data may be, for example, pressure data received as a part of the vehicle data at block **405** of the method **400**. In particular, the pressure data represents the air pressure of the cavity in which the sensing arrangement **120**, and more particularly, the pressure sensor **220** is disposed.

[0100] At block **810**, the server **104** determines the load on the tire **116**. In particular, the shape (i.e., the width and amplitude) of the deformation peak **642** are related to the pressure of the tire **116** as well as the load on the tire. For example, for a given load, a higher pressure in the tire **116** results in a smaller deformation and a smaller contact length **604** with the surface **600** on which the tire **116** is moving. Similarly, for a given pressure in the tire **116**, a higher load results in a larger deformation and a larger contact length **604** with the surface **600** on which the tire **116** is moving.

[0101] In particular, the load on the tire **116** may be computed as the product of the area in contact with the road and the pressure. Accordingly, the server **104** may obtain the contact length determined at block **425** and compute the load on the tire **116** as the product of the contact length, a width of the tire **116**, and the pressure obtained at block **805**. The width of the tire **116** may be a predetermined measurement stored, for example in the memory **304** of the server **104** or may be received from the monitoring hub **124** as part of the vehicle data received at block **405**.

[0102] At block **815**, the server **104** determines whether the load computed at block **810** meets a hazard and/or risk condition for the tire **116**. For example, if the load on the tire **116** exceeds a maximum recommended load, the server **104** may identify a risk condition associated with the load on the tire **116**. In some examples, in addition to the load computed at block **810**, the server **104** may obtain historical loads for the tire **116**, for example over a predefined period (e.g., 1 day, 10 days, 1 month, etc.). The server **104** may then determine whether the current load (i.e., as determined at block **810**), together with the historical load on the tire **116** constitute a risk condition. For example, if the load is above a threshold load (e.g., within a threshold percentage of the maximum recommended load for the tire **116**), and the tire **116** has been subject to similar excessive loads for at least a threshold amount of the predefined period (e.g., a threshold percentage of the predefined period, a threshold number of times over the predefined period, etc.), then the server **104** may determine that a risk condition has been met. If the tire **116** has not been subject to excessive loads over the predefined period, then the server **104** may determine that the tire **116** is not yet at a risk condition which should be noted. In other examples, other load risk conditions are also contemplated.

[0103] If, at block **815**, the determination is affirmative, that is, the server **104** determines that a risk condition is met based on the load determined at block **810**, then the server **104** proceeds to block **820**. At block **820**, the server **104** identifies a load risk for the tire **116**. The server **104** may transmit a notification or an alert to an operator of the vehicle **112** to notify the operator of the load risk on the tire **116**. For example, the notification may be an email notification, a text message, a push notification, or the like. In other examples, the server **104** may transmit the notification of the load risk to the monitoring hub **124**, which may in turn provide the notification of the load risk to the operator (e.g., at the monitoring hub **124** itself, or by transmitting notification to a mobile device or the like for the operator). In some examples, the server **104** may handle the load risk according to the urgency of the identified risk. For example, if the load exceeds the maximum recommended load and hence may cause rapid and imminent failure of the tire **116**, the server **104** may send an urgent alert notifying the operator and other parties as necessary. If the historical load indicate a long-term risk of faster than normal wear over the lifespan of the tire **116**, then the server **104** may provide a simple notification, and/or may save the notification for inclusion in a periodic (e.g., daily, weekly, etc.) status report or the like.

[0104] After identifying the load risk at block **820**, or if the server **104** determines at block **815** that no risk condition is detected based on the load, the server **104** proceeds to block **825**.

[0105] At block **825**, the server **104** obtains historical contact lengths for the tire **116**. For example, the historical contact lengths for a given tire **116** may be stored in the memory **304**, and more particularly, in the repository **316**. In particular, contact length variation over time may be an indicator of excessive wear on a tire. In some examples, in order to compare contact lengths under similar conditions, the server **104** may retrieve contact lengths for the tire **116** when the tire **116** is under similar loads (e.g., within a threshold percentage) as computed at block **810**.

[0106] At block **830**, the server **104** determines whether the contact length for the tire **116**, in view of the historical contact lengths for the tire **116**, meets a hazard and/or risk condition for the tire **116**. For example, if the contact length for the tire **116** has increased by a threshold percentage over a predefined period (e.g., 1 month, over the lifetime of the tire **116**, etc.), the server **104** may determine a risk condition has been met. In other examples other contact length risk conditions are also contemplated.

[0107] If, at block **830**, the determination is affirmative, that is, the server **104** determines that a risk condition is met based on the contact length and historical contact lengths for the tire **116**, then the server **104** proceeds to block **835**. At block **835**, the server **104** identifies a contact length risk for the tire **116**. The server **104** may transmit a notification or alert to an operator of the vehicle **112**, or to the monitoring hub **124**, which may in turn provide the notification to the operator.

[0108] After identifying the contact length risk at block **835**, or if the server **104** determines at block **830** that no risk condition is detected based on the contact length, the server **104** proceeds to block **840**.

[0109] At block **840**, the server **104** obtains temperature data for the tire **116**. The temperature data may be, for example, temperature data received as a part of the vehicle data at block **405** of the method **400**. In particular, the temperature data represents the temperature of the tire **116**. Further, since the temperature sensor **216** is arranged in the sensing arrangement to be adjacent to the inner side **200** of the tire **116**, the temperature data is representative of the material forming the tire **116** itself, rather than the temperature of the air cavity of the tire **116**. This is in contrast to typical temperature sensors which are disposed at the valve stem of the tire **116**, as the operational range of temperature sensors at the valve stem does not capture the tire material, and accordingly, may vary from the temperatures experienced by the tire **116** itself.

[0110] At block **845**, the server **104** determines whether the temperature experienced by the tire **116** meets a hazard and/or risk condition for the tire **116**. For example, if the temperature of the tire **116** exceeds a threshold temperature (e.g., a critical temperature such as about 90° C. which the tire **116** should not exceed), the server **104** may identify a risk condition associated with the temperature of the tire **116**. In some examples, in addition to the temperature obtained at block **840**, the server **104** may obtain historical temperatures for the tire **116**, for example over a predefined period. The server **104** may then determine whether the current temperature, together with the historical temperature of the tire constitute a risk condition. For example, increased maximum temperatures over time (i.e., based on a maximum temperature over a trip, as the tire **116** increases in temperature with movement), may indicate wear and potential failure of the tire **116**. In other examples, rapid changes in temperature for a given trip (e.g., within a 1 minute or 5-minute span or the like) may also indicate an imminent risk condition. In other examples, other temperature risk conditions are also contemplated.

[0111] If, at block **845**, the determination is affirmative, that is, the server **104** determines that a risk condition is met based on the temperature obtained at block **840**, then the server **104** proceeds to block **850**. At block **850**, the server **104** identifies a temperature risk for the tire **116**. The server **104** may transmit a notification or alert to an operator of the vehicle **112**, or to the monitoring hub **124**, which may in turn provide the notification to the operator.

[0112] After identifying the temperature risk at block **850**, or if the server **104** determines at block **845** that no risk condition is detected based on temperature, the server **104** proceeds to block **855**.

[0113] At block **855**, the server **104** may aggregate the load, contact length and temperature performance factors to determine overall tire performance or working condition assessment. For example, if the server **104** determines that the tire data obtained at block **405** for the given tire **116** does not indicate any imminent or long-term risk conditions, then the server **104** may determine that the tire **116** is in working condition. In some examples, the server **104** may transmit a notification that the working condition of the tire **116** is in an acceptable state to an operator of the vehicle **112**, or to the monitoring hub **124**, which may in turn provide the notification to the operator. If one or more risk conditions were identified, then the working condition assessment may include an indication of the identified risks. In some examples, if the working condition assessment of the tire **116** includes an identification of one or more risk conditions as identified at blocks **820**, **835**, or **850**, then in some examples, the notification or alerts may be transmitted as a single notification as part of the working condition assessment, rather than individually at blocks **820**, **835**, and **850**. In further examples, the working condition assessment of the tire **116** may be stored for inclusion in a periodic status report for the vehicle or the like.

[0114] In addition to the single tire performance analysis, the server **104** may determine vehicle performance for the vehicle **112** as a whole. For example, referring to FIG. **9**, a flowchart of an example method **900** of determining vehicle performance is depicted. In some examples, the operations of the method **900** may be performed in an order other than that depicted.

[0115] At block **905**, the server **104** obtains the load applied to each of the tires **116**, for example as determined at block **810** of the method **800**. The server **104** may then determine an overall load for the vehicle **112**, as well as a load distribution of the overall load on the tires **116**. For example, the server **104** may express the load distribution for each tire **116** as a percentage of the overall load.

[0116] At block **910**, the server **104** determines whether the load distribution on the tires **116** meets a hazard and/or risk condition for the vehicle **112**. For example, if the load distribution is expected to be substantially equal between each of the tires **116**, and the load distribution indicates an uneven distribution (e.g., more than a threshold percentage differential between respective load distributions of each tire **116**), then the server **104** may identify a load distribution risk condition. Preferably, the thresholds may be tuned to account for differences in load distribution for a different number of passengers (e.g., four adults vs. one adult in the driver's seat) or other day-to-day variable factors. Accordingly, in some examples, the thresholds for load distribution differences may vary according to the overall load on the vehicle **112**.

[0117] In other examples, the load distribution amongst the tires **116** may be expected to be different. For example, when the vehicle is a semi-trailer, the server **104** may expect that the trailer-bearing tires **116** may have a higher load relative to the cab-bearing tires **116**. The difference in tires **116** may be predetermined and stored for example in the memory **304** or the like. In such examples, the server **104** may additionally store an expected or ideal load distribution. Accordingly, the server **104** may compare the load distribution determined at block **905** to the expected or ideal load distribution. If the load distribution varies by more than a threshold percentage from the expected or ideal load distribution, the server **104** may identify a load distribution risk condition at block **910**.

[0118] Further, in some examples, the server **104** may obtain historical load distribution for the vehicle **112** over a predefined period, such as based on a current trip of the vehicle **112**. In particular, a differing load distribution over a single trip may indicate a shifting load within the vehicle, which may indicate unsecured loads or unsafe conditions, for example due to tipping risks of large vehicles when turning. In other examples, other load distribution risk conditions are also contemplated.

[0119] If, at block **910**, the determination is affirmative, that is, the server **104** determines that a risk condition is met based on the load distribution determined at block **905**, then the server **104** proceeds to block **915**. At block **915**, the server **104** identifies a load distribution risk for the vehicle **112**. The server **104** may transmit a notification or alert to an operator of the vehicle **112**, or to the monitoring hub **124**, which may in turn provide the notification to the operator.

[0120] After identifying the load distribution risk at block **915**, or if the server **104** determines at block **910** that no risk condition is detected based on load distribution, the server **104** proceeds to block **920**.

[0121] At block **920**, the server **104** checks the deformation data for each of the tires **116** for any anomalous patterns. An anomalous pattern is a pattern (e.g., a pulse or other shift) away from the baseline, and which does not conform to the repeating pattern (e.g., based on magnitude and width, or the like). For example, the server **104** may identify the pulse **704-2** as depicted in FIG. **7** as an anomalous pattern.

[0122] At block **925**, the server **104** determines whether the anomalous pattern (or a similar anomalous pattern) is also detected in the other tires **116** of the corresponding vehicle **112**. That is, the server **104** may check for an analogous anomalous pattern in the deformation data of each of the other tires **116**. For example, a pattern may be determined to be analogous if has similar proportions (e.g., magnitude and/or width) and/or if it occurs within a threshold time of the anomalous pattern (e.g., within 1 second, etc.).

[0123] In particular, if at least one of the other tires **116** has deformation data with an analogous anomalous pattern, then the server **104** may assume that an external event has occurred. For example, if the vehicle **112** traverses a pothole (or other bump, imperfection, or defect in the surface on which the vehicle **112** is travelling), the tires **116** may deform in a different manner from the repeating pulse **630**. Since the tires **116** are situated at different locations on the vehicle **112**, each tire **116** may experience a different anomalous deformation. For example, corresponding front and rear tires **116** traversing the defect may detect the anomalous deformation at offset times (e.g., offset by half a second). In some examples, if the defect is sufficiently small, the tires **116** on the opposing side of the vehicle **112** may experience little to no anomalous deformation, and accordingly, an analogous anomalous pattern may not be detected in the deformation data for the opposing tires **116**. In other examples, the defect may be sufficiently large such that the tires **116** on the opposing side of the vehicle **112** do experience an anomalous deformation. However, the opposing tires **116** may deform differently based on their distance from the defect. Accordingly, the anomalous pattern may not be proportional, but may still occur within the threshold time of the anomalous pattern.

[0124] In such examples, the server **104** may determine that the anomaly in the deformation data was likely caused due to an external event or surface defect which affected each of the tires **116**, rather than a simultaneous failure or other internal incident of each of the tires **116**. Accordingly, if the determination at block **925** is affirmative, the server **104** may proceed to block **935**. In some examples, the server **104** may note the anomalous pattern and a time of occurrence for comparison of tire data for each of the tires **116**, for example to determine whether the external event affected the integrity and/or performance of any of the tires **116**.

[0125] If an analogous anomalous pattern is not detected in any of the other tires **116** of the corresponding vehicle **112**, then the server **104** proceeds to block **930**. At block **930**, the server **104** identifies an anomalous event for the given tire **116** having the anomalous pattern. In some examples, the server **104** may note the anomalous pattern and a time of occurrence for comparison of the tire data for the given tire **116** to determine whether the anomalous event affected the integrity and/or performance of the given tire **116**.

[0126] At block **930**, the server **104** may additionally transmit a notification or alert to an operator of the vehicle **112**, or to the monitoring hub **124**, which in turn may provide the notification to the operator. For example, the notification may include a prompt to manually inspect the tire **116** experiencing the anomalous event (e.g., to check for nails or sharp objects impaling the tire **116** or the like). In some examples, the notification provided to the operator may depend on the severity (e.g., magnitude and width) of the anomalous event.

[0127] At block **935**, the server **104** may additionally determine other operational parameters of the vehicle **112**. For example, since a peak in the deformation data occurs each time the deformation sensor **212** passes through the contact length **604**, the frequency of the peaks corresponds to the speed at which the tire **116** is rotating. Accordingly, based on the frequency of the peaks and the radius of the tire **116**, the server **104** may determine a rotation speed of the tires **116**, and hence of the vehicle **112**. Further, the server **104** may determine an acceleration of the tires **116** (and hence of the vehicle **112**) based on a change in frequency of peaks (i.e., the repeating pattern) in the deformation data.

[0128] For example, referring to FIGS. **10**A and **10**B, a first example plot **1000** depicts deformation data when the vehicle **112** is accelerating, while a second example plot **1010** depicts deformation data when the vehicle **112** is decelerating.

[0129] Returning again to FIG. **9**, at block **940**, the server **104** may assemble a vehicle performance or working condition assessment. In particular, the server **104** may aggregate the load distribution, pattern analysis, and operational parameter factors for the vehicle.

[0130] For example, if the server **104** determines that the vehicle data obtained at block **405** does not indicate any imminent or long-term risk conditions, the server **104** may determine that the vehicle **112** is in an acceptable working condition. The server **104** may transmit a notification of the acceptable working condition to an operator of the vehicle **112**, or to the monitoring hub **124**, which may in turn provide the notification to the operator. If one or more risk conditions were identified, then the working condition assessment may include an indication of the identified risks. In some examples, the risks may be identified as part of the working condition assessment at block **940**, rather than individually at blocks **915** and **930**. Further in some examples, the tire working condition assessments for each of the tires (i.e., as obtained at block **855** of the method **800**) may be aggregated and identified as part of the vehicle working condition assessment at block **940**, rather than individually.

[0131] The vehicle working condition assessment may be transposed to a periodic status report for the vehicle which may be transmitted to the operator of the vehicle and/or the monitoring hub **124** periodically.

[0132] As will be appreciated, variations to the above-described systems and methods are also possible. For example, some or all of the analysis described above as being performed by the server **104** may be performed by the monitoring hub **124** locally, to provide data including when communication between the monitoring hub **124** and the server **104** is interrupted. For example, the operational parameters, such as vehicle speed, acceleration and deceleration may be computed by the monitoring hub **124** for feedback to an operator of the vehicle **112**. In still further examples, some or all of the analysis described above may be performed by the processor **230** of the sensing arrangement **120**.

[0133] Further, in some examples, the tire data for each for each of the tires may be annotated and added to a training set to train a machine-learning based model, for example to identify other potential risks for individual tires or for the vehicle based on trends and correlations between the deformation data, the temperature data, and the pressure data. For example, after detecting anomalous events, both affecting a single tire and affecting more than one tire, the deformation data for each of the tires may be annotated with the type of anomalous event experienced (e.g., speed bump, pothole, nail in tire, etc.) to allow a trained model to predict the type of anomalous event based on the deformation data. The tire data may additionally be used to develop models for tire wear, to predict tire failure, to optimize fuel efficiency, and the like. Such information may be used, for example to manage a fleet of vehicles, to manage tire changes in performance racing, inform tire design, and other applications.

[0134] In some examples, the tire data may be supplied to an autonomous vehicle decision module, to better inform autonomous vehicle systems of road conditions as detected by the tires. For example, such tire data may be indicative of ice on the road, or similar, which may affect driving speeds, acceleration, braking, steering, and other vehicle parameters selected by the autonomous vehicle system.

[0135] The scope of the claims should not be limited by the embodiments set forth in the above examples but should be given the broadest interpretation consistent with the description as a whole.

1. A sensing arrangement for a tire, the sensing arrangement comprising:
- a substrate configured to couple the sensing arrangement to an inner side of the tire;
- a deformation sensor supported by the substrate and configured to collect deformation data representing deformation at the inner side of the tire; and
- a control module configured to transmit the deformation data collected by the deformation sensor to a recipient device.

2. The sensing arrangement of claim **1**, wherein the deformation sensor is configured to:
- detect a first deformation shift at an entry point of a contact length of the tire with a surface;
- detect a deformation peak over the contact length of the tire with the surface; and
- detect a second deformation shift at an exit point of the contact length of the tire with the surface.

3. The sensing arrangement of claim **1**, further comprising one or more of:
- a temperature sensor supported by the substrate adjacent to the inner side of the tire, the temperature sensor configured to measure a temperature at the inner side of the tire; and
- a pressure sensor supported by the substrate, the pressure sensor configured to measure a pressure within the tire.

4. (canceled)

5. (canceled)

6. (canceled)

7. The sensing arrangement of claim **1**, wherein the deformation sensor has a length exceeding a length of a tread pattern of the tire.

8. The sensing arrangement of claim **1**, further comprising a vibration damping portion configured to isolate the control module from vibrations experienced by the substrate.

9. A tire monitoring system for monitoring a set of tires of a vehicle, the system comprising:
- a set of sensing arrangements, each sensing arrangement configured to couple to an inner side of one of the tires in the set to collect deformation data representing deformation at the inner side of the tire; and
- a monitoring hub configured to aggregate the deformation data from each sensing arrangement in the set and transmit the aggregated deformation data to a server.

10. A server comprising:
- a memory;
- a communications interface; and
- a processor interconnected with the memory and the communications interface, the processor configured to:
  - obtain deformation data representing deformation of a tire over a series of rotations;
  - detect a repeating pattern in the deformation data;
  - determine, based on the repeating pattern, a contact angle of the tire;
  - determine a contact length as a product of the contact angle and a radius of the tire; and
  - determine a working condition assessment of the tire based on the contact length.

11. The server of claim **10**, wherein to determine the contact angle, the processor is configured to:
- determine a contact time based on a width of an instance of the repeating pattern;
- determine a revolution time based on a distance between the instance of the repeating pattern and a subsequent instance of the repeating pattern; and
- compute the contact angle based on a ratio of the contact time to the revolution time.

12. The server of claim **11**, wherein the processor is configured to determine the width of the instance of the repeating pattern based on a full-width-half-maximum distance of the instance of the repeating pattern.

13. (canceled)

14. The server of claim **10**, wherein the processor is further configured to determine one or more of:
- a rotation speed of the tire based on a frequency of the repeating pattern in the deformation data; and
- an acceleration of the tire based on a change in frequency of the repeating pattern in the deformation data.

15. (canceled)

16. The server of claim **10**, wherein the processor is further configured to:
- obtain further deformation data for a set of tires of a vehicle, the set of tires including the tire;
- detect an anomalous pattern in the deformation data; and
- when no analogous anomalous pattern is detected in the further deformation data, identify an anomalous event for the tire.

17. The server of claim **10**, wherein the processor is further configured to:
- obtain pressure data representing an internal tire pressure; and
- determine a load on the tire based on the contact length and the pressure data.

18. The server of claim **17**, wherein the processor is further configured to:
obtain further deformation data and further pressure data for a set of tires of a vehicle, the set of tires including the tire; and
determine a load distribution between the tires in the set.

19. A method of monitoring a tire, the method comprising:
obtaining deformation data representing deformation of the tire over a series of rotations;
detecting a repeating pattern in the deformation data;
determining, based on the repeating pattern, a contact angle of the tire;
determining a contact length as a product of the contact angle and a radius of the tire; and
determining a working condition assessment of the tire based on the contact length.

20. The method of claim **19**, wherein determining the contact angle comprises:
determining a contact time based on a width of an instance of the repeating pattern;
determining a revolution time based on a distance between the instance of the repeating pattern and a subsequent instance of the repeating pattern; and
computing the contact angle based on a ratio of the contact time to the revolution time.

21. The method of claim **20**, wherein determining the width of the instance of the repeating pattern based on a full-width-half-maximum distance of the instance of the repeating pattern.

22. (canceled)

23. The method of claim **19**, further comprising determining one or more of:
a rotation speed of the tire based on a frequency of the repeating pattern in the deformation data; and
an acceleration of the tire based on a change in frequency of the repeating pattern in the deformation data.

24. (canceled)

25. The method of claim **19**, further comprising:
obtaining further deformation data for a set of tires of a vehicle, the set of tires including the tire;
detecting an anomalous pattern in the deformation data; and
when no analogous anomalous pattern is detected in the further deformation data, identifying an anomalous event for the tire.

26. The method of claim **19**, further comprising:
obtaining pressure data representing an internal tire pressure; and
determining a load on the tire based on the contact length and the pressure data.

27. The method of claim **26**, further comprising:
obtaining further deformation data and further pressure data for a set of tires of a vehicle, the set of tires including the tire; and
determining a load distribution between the tires in the set.

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