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### Automatic event capturing for autonomous vehicle driving

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#### Abstract

This application is directed to collecting event-based vehicle traffic data to facilitate driving a vehicle. A computer system includes sensors that are positioned on a fixed installation at a road, one or more processors, and memory. The computer system monitors, using the plurality of sensors on the fixed installation, vehicle traffic data (e.g., associated with one or more events) in a zone of interest of the road over a period of time to generate historical traffic data. The computer system uses the historical traffic data to train a driving model of an at least partially autonomous vehicle. The computer system sends the driving model to one or more vehicles. The driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a similar zone of interest.

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Background/Summary

RELATED APPLICATIONS (1) This application claims priority to (i) U.S. Provisional Application No. 63/544,425, filed Oct. 16, 2023, titled “Motion Controlling for Autonomous Vehicles” and (ii) U.S. Provisional Application No. 63/636,090, filed Apr. 18, 2024, titled “Centralized Prediction and Planning Using V2X for Lane Platooning and Intersection Vehicle Behavior Optimizations and Lane Change Decision-Making by Combining Infrastructure and Vehicle Intelligence,” each of which is hereby incorporated by reference herein in its entirety. (2) This application is related to the following applications, all of which are incorporated by reference herein in their entireties: U.S. patent application Ser. No. 18/808,067, filed Aug. 18, 2024, titled “Detecting Road and Weather

Conditions for Vehicle Driving”; and U.S. patent application Ser. No. 18/808,069, filed Aug. 18, 2024, titled “Motion Planning for Autonomous Vehicle Driving Using Vehicle-to-Infrastructure Communication.”

## TECHNICAL FIELD

(1) The present application generally relates to vehicle technology, and more particularly to, methods, systems, and non-transitory computer readable storage media for collecting vehicle traffic data that can be used onboard or offboard to improve decision making in autonomous vehicles.

## BACKGROUND

(2) Vehicles are now capable of self-driving with different levels of autonomy. Each of these levels is characterized by the relative amount of human and autonomous control. For example, The Society of Automotive Engineers (SAE) defines 6 levels of driving automation ranging from 0 (fully manual) to 5 (fully autonomous). These levels have been adopted by the U.S. Department of Transportation. Autonomous vehicles provide numerous advantages including: (1) lowering the number of vehicles on the roads, (2) more predictable and safer driving behavior than human driven vehicles, (3) less emissions if there are fewer vehicles on the road, and if they are electrically powered, (4) improved travel efficiency, fuel economy, and traffic safety if they are controlled by computers, (5) increased lane capacity, (6) shorter travel times, and (7) increased mobility for users who are incapable of driving.

(3) There are numerous advantages of autonomous vehicles, including: (1) lowering the number of vehicles on the roads (most privately owned vehicles are driven a small fraction of the time); (2) more predictable and safer driving behavior than human driven vehicles; (3) less emissions if more vehicles are electrically powered; (4) improved fuel efficiency; (5) increased lane capacity; (6) shorter travel times; and (7) mobility for users who are incapable of driving.

(4) One of the key obstacles facing the autonomous vehicle industry is the complexity and unpredictability of road and traffic conditions. This makes it difficult to train autonomous vehicles for every possible rare condition or event that the vehicle may encounter while driving. For example, occasionally, human drivers may need to react to extraordinary or rare events, such as a package falling off a truck or a lane closure. In these situations, human drivers are often able to instinctively react to avoid harm to themselves and their vehicle, but unless the autonomous driving model has been trained for such a rare event, the vehicle may not know how to react.

(5) Currently, autonomous vehicles are equipped with sensors that are primarily used for object (e.g., obstacle) detection. Fleet operators often collect large amounts of data from individual vehicles in order to learn from existing road and traffic conditions. However, these data tend to be limited only to the perception of the individual vehicles. It would be beneficial to have a mechanism to utilize the large amounts of data collected from individual vehicles in a productive manner.

## SUMMARY

(6) Some embodiments of the present disclosure are directed to methods, systems, and non-transitory computer readable storage media for collecting vehicle traffic associated with events to facilitate autonomous vehicle driving. In accordance with some embodiments of this application is a realization that road agent models and traffic models can be applied on large scale simulation platforms to utilize information of large area detection coverage of a road (e.g., an entire segment of a freeway, or an intersection zone, or a lane merge zone). Particularly, data should be recorded in an automatic and selective way to avoid having to analyze large amounts of repetitive data. In accordance with some embodiments of this application is a realization that systems and methods for automatically identifying target events and collecting relevant event data for use in improving onboard or offboard decision making algorithms applied by autonomous vehicles. The relevant event data may be applied to develop road agent models and traffic models on large scale simulation platforms in a reliable and cost-effective manner.

(7) According to some aspects of the present disclosure, sensors are disposed at a fixed installation (e.g., an infrastructure, having at a fixed location), and configured to directly monitor and gather data (e.g., traffic-related parameters). For example, an installation may be located at an on-ramp area of a road, at a lane-merge area, or at a road intersection. Compared to data collected by individual vehicles using vehicle sensors, traffic information collected by the sensors disposed at the fixed installation tend to be more detailed and instantaneous. The sensors disposed at the fixed installation may be statically (e.g., fixedly or immovably) positioned, have better detection coverage, and focus on a fixed area of a road.

(8) As disclosed, in some embodiments, the fixed installation includes a data processing unit that is attached to the installation. The data processing unit is configured to process data collected by the sensors disposed at the fixed installation, including automatically capturing driving scenarios or “events” that are associated with complex decision making processes such as collision avoidance, post-accident reaction, and negotiation among different traffic streams. As used herein, in some embodiments, an event refers to a situation that can impact the driving decision of an autonomous vehicle.

(9) As disclosed, in some embodiments, the data processing unit executes an automatic scenario capturing system that is configured to implement tasks for one or more of event detection, scenario classification, data abstraction, and data transmission. In some instances, vehicles involved in the scenario have the option to receive the scenario data immediately (e.g., at no cost). In some embodiments, data captured from an event can be stored in a cloud-based data pool, which can be shared to autonomous driving entities (e.g., as a data service).

(10) Accordingly, the systems and/or methods disclosed herein advantageously improve decision making modules in autonomous vehicles by continuously generating training data of driving scenarios at a fairly low cost. Not only is the data collected by sensors positioned at a fixed installation of high quality, but it is also particularly suited for developing large-scale road agent models and traffic models. Relevant sensor data are selectively stored and streamed to a server that trains an autonomous vehicle driving model, thereby conserving resources (e.g., memory space and communication bandwidth).

(11) In one aspect, a method for automatic event capturing is implemented at a computer system that includes a plurality of sensors that are positioned on a fixed installation at a road, one or more processors, and memory. The method includes monitoring, by the plurality of sensors on the fixed installation, vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data. The method includes using the historical traffic data to train a driving model of an at least partially autonomous vehicle. The method also includes sending the driving model to one or more vehicles, where the driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a similar zone of interest.

(12) In some embodiments, monitoring the vehicle traffic data in the zone of interest of the road includes, in accordance with a determination that a first event has occurred: triggering recording of the first event via the plurality of sensors; generating event data based on the recording; and adding the event data to a corpus of data to generate the historical traffic data.

(13) In some embodiments, the method includes temporarily storing road condition monitoring data corresponding to a pre-defined buffer period. Triggering recording of the first event includes adding at least a portion of the temporarily stored road condition monitoring data to the first event recording.

(14) In some embodiments, the recording comprises a first data format. Generating the event data based on the recording includes converting the recording having the first data format to the event data having a second data format that is different from the first data format.

(15) In some embodiments, the method includes receiving vehicle operational data from one or more vehicles that are traveling in the zone of interest of the road over the period of time, and using

the vehicle operational data to generate the historical traffic data.

(16) In some embodiments, the first event involves a first vehicle. The method further includes transmitting the recording of the first event to the first vehicle.

(17) According to another aspect of the present application, a computer system includes a plurality of sensors that are positioned on a fixed installation at a road, one or more processors, and memory coupled to the one or more processors. The memory storing instructions that, when executed by the one or more processors, cause the computer system to perform any of the methods for automatic event capturing as disclosed herein.

(18) According to another aspect of the present application, a non-transitory computer readable storage medium stores instructions configured for execution by a computer system that includes a plurality of sensors that are positioned on a fixed installation at a road, one or more processors, and memory. The instructions, when executed by the one or more processors, cause the computer system to perform any of the methods for automatic event capturing as disclosed herein.

(19) Note that the various embodiments described above can be combined with any other embodiments described herein. The features and advantages described in the specification are not all inclusive and, in particular, many additional features and advantages will be apparent to one of ordinary skill in the art in view of the drawings, specification, and claims. Moreover, it should be noted that the language used in the specification has been principally selected for readability and instructional purposes and may not have been selected to delineate or circumscribe the inventive subject matter.

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## Description

### BRIEF DESCRIPTION OF THE DRAWINGS

(1) The accompanying drawings, which are included to provide a further understanding of the embodiments, are incorporated herein, constitute a part of the specification, illustrate the described embodiments, and, together with the description, serve to explain the underlying principles.

(2) FIG. 1 is an example vehicle driving environment for a plurality of vehicles, in accordance with some embodiments.

(3) FIG. 2 is a block diagram of an example vehicle configured to be driven with a certain level of autonomy, in accordance with some embodiments.

(4) FIG. 3 is a block diagram of an example server for monitoring and managing vehicles in a vehicle driving environment, in accordance with some embodiments.

(5) FIG. 4 is a block diagram of a machine learning system for training and applying vehicle data processing models for facilitating at least partial autonomous driving of a vehicle, in accordance with some embodiments.

(6) FIG. 5A is a structural diagram of an example neural network applied to process vehicle data in a vehicle data processing model, in accordance with some embodiments, and FIG. 5B is an example node in the neural network, in accordance with some embodiments.

(7) FIG. 6 is a block diagram of a computer system associated with an installation, in accordance with some embodiments.

(8) FIG. 7 illustrates a scenario capturing system, in accordance with some embodiments.

(9) FIGS. 8A to 8C provide a flowchart of an example process for automatic event capturing, in accordance with some embodiments.

(10) Like reference numerals refer to corresponding parts throughout the several views of the drawings.

### DETAILED DESCRIPTION

(11) Reference will now be made in detail to specific embodiments, examples of which are illustrated in the accompanying drawings. In the following detailed description, numerous non-

limiting specific details are set forth in order to assist in understanding the subject matter presented herein. But it will be apparent to one of ordinary skill in the art that various alternatives may be used without departing from the scope of the claims and the subject matter may be practiced without these specific details. For example, it will be apparent to one of ordinary skill in the art that the subject matter presented herein can be implemented on many types of electronic devices with digital video capabilities.

(12) Various embodiments of this application are directed to collecting event-related vehicle traffic data that can be used in onboard or offboard decision making by autonomous vehicles. In some embodiments, an event refers to a situation that impacts the driving decision of an autonomous vehicle. In some embodiments, a computer system includes a plurality of sensors that are positioned on a fixed installation (e.g., an infrastructure) at a road, one or more processors, and memory. In some embodiments, the computer system (e.g., a microcontroller unit) is physically co-located at the fixed installation. In some embodiments, the computer system includes one or more distinct systems located at distinct locations of the road. For example, multiple installations, each having respective sensors, may be positioned along a stretch of a road (e.g., at intervals of every one kilometer, three kilometers, or five kilometers).

(13) The plurality of sensors can include one or more cameras, one or more microphones, one or more inductive loop detectors, a radio detection and ranging (RADAR) sensor, an infrared sensor, and one or more ultrasonic sensors. The computer system monitors (e.g., continuously, periodically, at regular intervals), using the plurality of sensors on the fixed installation, vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data.

(14) In some embodiments, the computer system receives vehicle operational data from one or more vehicles that are traveling in the zone of interest of the road over the period of time (e.g., via a wireless communication network, such as a 5G network and uses the vehicle operational data to generate the historical traffic data. The computer system uses the historical traffic data to at least partially train a driving model of an at least partially autonomous vehicle. The computer system sends the driving model to one or more vehicles, where the driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a similar zone of interest.

(15) In some embodiments, the computer system monitors the vehicle traffic data in the zone of interest of the road. In accordance with a determination (e.g., by the computer system) that a first event has occurred, the computer system triggers (e.g., automatically, without user intervention) recording of the first event via the plurality of sensors, generates event data based on the recording, and adds the event data to a corpus of data to generate the historical traffic data. In some embodiments, the computer system determines that the first event has occurred when the vehicle traffic data satisfies a first set of (e.g., one or more) criteria. In some embodiments, the computer system determines that the first event has occurred by comparing the vehicle traffic data against a set of predefined rules to determine whether the vehicle traffic data satisfies a rule of the set of predefined rules. In some embodiments, the computer system determines that the first event has occurred by inputting the vehicle traffic data into a deep neural network that is configured to determine whether the vehicle traffic data satisfies one or more criteria for occurrence of the first event.

(16) In some embodiments, generating the event data based on the recording includes selecting, for a respective vehicle of one or more vehicles in the first event, a respective value from a predetermined set of values (e.g., values such as “1”, “2”, and “3”) for a first index (e.g., a vehicle behavior change index) corresponding to a behavior of the respective vehicle in the first event. In some embodiments, determining the aggregated value includes aggregating one or more respective values for the first index, from the one or more vehicles in the first event, to obtain the aggregated value. In some embodiments, in accordance with a determination that the aggregated value satisfies a threshold value, the computer system retains the recording and generates the event data based on

the recording.

(17) FIG. 1 is an example vehicle driving environment **100** having a plurality of vehicles **102** (e.g., vehicles **102P**, **102T**, and **102V**), in accordance with some embodiments. Each vehicle **102** has one or more processors, memory, a plurality of sensors, and a vehicle control system. The vehicle control system is configured to sense the vehicle driving environment **100** and drive on roads having different road conditions. The plurality of vehicles **102** may include passenger cars **102P** (e.g., sport-utility vehicles and sedans), vans **102V**, trucks **102T**, and driver-less cars. Each vehicle **102** can collect sensor data and/or user inputs, execute user applications, present outputs on its user interface, and/or operate the vehicle control system to drive the vehicle **102**. The collected data or user inputs can be processed locally (e.g., for training and/or for prediction) at the vehicle **102** and/or remotely by one or more servers **104**. The one or more servers **104** provide system data (e.g., boot files, operating system images, and user applications) to the vehicle **102**, and in some embodiments, process the data and user inputs received from the vehicle **102** when the user applications are executed on the vehicle **102**. In some embodiments, the vehicle driving environment **100** further includes storage **106** for storing data related to the vehicles **102**, servers **104**, and applications executed on the vehicles **102**.

(18) For each vehicle **102**, the plurality of sensors includes one or more of: (1) a global positioning system (GPS) sensors; (2) a light detection and ranging (LiDAR) scanner; (3) one or more cameras; (4) a radio detection and ranging (RADAR) sensor; (5) an infrared sensor; (6) one or more ultrasonic sensors; (7) a dedicated short-range communication (DSRC) module; (8) an inertial navigation system (INS) including accelerometers and gyroscopes; (9) an inertial measurement unit (IMU) for measuring and reporting acceleration, orientation, angular rates, and other gravitational forces; and/or (10) an odometry sensor. In some embodiments, a vehicle **102** includes a 5G communication module to facilitate vehicle communication jointly with or in place of the DSRC module. The cameras are configured to capture a plurality of images in the vehicle driving environment **100**, and the plurality of images are applied to map the vehicle driving environment **100** to a 3D vehicle space and identify a location of the vehicle **102** within the environment **100**. The cameras also operate with one or more other sensors (e.g., GPS, LiDAR, RADAR, and/or INS) to localize the vehicle **102** in the 3D vehicle space. For example, the GPS identifies a geographical position (geolocation) of the vehicle **102** on the Earth, and the INS measures relative vehicle speeds and accelerations between the vehicle **102** and adjacent vehicles **102**. The LiDAR scanner measures the distance between the vehicle **102** and adjacent vehicles **102** and other objects. Data collected by these sensors is used to determine vehicle locations determined from the plurality of images or to facilitate determining vehicle locations between two images.

(19) The vehicle control system includes a plurality of actuators for at least steering, braking, controlling the throttle (e.g., accelerating, maintaining a constant velocity, or decelerating), and transmission control. Depending on the level of automation, each of the plurality of actuators (or manually controlling the vehicle, such as by turning the steering wheel) can be controlled manually by a driver of the vehicle, automatically by the one or more processors of the vehicle, or jointly by the driver and the processors. When the vehicle **102** controls the plurality of actuators independently or jointly with the driver, the vehicle **102** obtains the sensor data collected by the plurality of sensors, identifies adjacent road features in the vehicle driving environment **100**, tracks the motion of the vehicle, tracks the relative distance between the vehicle and any surrounding vehicles or other objects, and generates vehicle control instructions to at least partially autonomously control driving of the vehicle **102**. Conversely, in some embodiments, when the driver takes control of the vehicle, the driver manually provides vehicle control instructions via a steering wheel, a braking pedal, a throttle pedal, and/or a gear lever directly. In some embodiments, a vehicle user application is executed on the vehicle and configured to provide a user interface. The driver provides vehicle control instructions to control the plurality of actuators of the vehicle control system via the user interface of the vehicle user application. By these means, the vehicle

**102** is configured to drive with its own vehicle control system and/or the driver of the vehicle **102** according to the level of autonomy.

(20) In some embodiments, autonomous vehicles include, for example, a fully autonomous vehicle, a partially autonomous vehicle, a vehicle with driver assistance, or an autonomous capable vehicle. Capabilities of autonomous vehicles can be associated with a classification system, or taxonomy, having tiered levels of autonomy. A classification system can be specified, for example, by industry standards or governmental guidelines. For example, the levels of autonomy can be considered using a taxonomy such as level 0 (momentary driver assistance), level 1 (driver assistance), level 2 (additional assistance), level 3 (conditional assistance), level 4 (high automation), and level 5 (full automation without any driver intervention) as classified by the International Society of Automotive Engineers (SAE International). Following this example, an autonomous vehicle can be capable of operating, in some instances, in at least one of levels 0 through 5. According to various embodiments, an autonomous capable vehicle may refer to a vehicle that can be operated by a driver manually (that is, without the autonomous capability activated) while being capable of operating in at least one of levels 0 through 5 upon activation of an autonomous mode. As used herein, the term “driver” may refer to a local operator or a remote operator. The autonomous vehicle may operate solely at a given level (e.g., level 2 additional assistance or level 5 full automation) for at least a period of time or during the entire operating time of the autonomous vehicle. Other classification systems can provide other levels of autonomy characterized by different vehicle capabilities.

(21) In some embodiments, the vehicle **102** drives in the vehicle driving environment **100** at level 5. The vehicle **102** collects sensor data from the plurality of sensors, processes the sensor data to generate vehicle control instructions, and controls the vehicle control system to drive the vehicle autonomously in response to the vehicle control instructions. Alternatively, in some situations, the vehicle **102** drives in the vehicle driving environment **100** at level 0. The vehicle **102** collects the sensor data and processes the sensor data to provide feedback (e.g., a warning or an alert) to a driver of the vehicle **102** to allow the driver to drive the vehicle **102** manually and based on the driver's own judgement. Alternatively, in some situations, the vehicle **102** drives in the vehicle driving environment **100** partially autonomously at one of levels 1-4. The vehicle **102** collects the sensor data and processes the sensor data to generate a vehicle control instruction for a portion of the vehicle control system and/or provide feedback to a driver of the vehicle **102**. The vehicle **102** is driven jointly by the vehicle control system of the vehicle **102** and the driver of the vehicle **102**. In some embodiments, the vehicle control system and driver of the vehicle **102** control different portions of the vehicle **102**. In some embodiments, the vehicle **102** determines the vehicle status. Based on the vehicle status, a vehicle control instruction of one of the vehicle control system or driver of the vehicle **102** preempts or overrides another vehicle control instruction provided by the other one of the vehicle control system or driver of the vehicle **102**.

(22) For the vehicle **102**, the sensor data collected by the plurality of sensors, the vehicle control instructions applied to the vehicle control system, and the user inputs received via the vehicle user application form a collection of vehicle data **112**. In some embodiments, at least a subset of the vehicle data **112** from each vehicle **102** is provided to one or more servers **104**. A server **104** provides a central vehicle platform for collecting and analyzing the vehicle data **112**, monitoring vehicle operation, detecting faults, providing driving solutions, and updating additional vehicle information **114** to individual vehicles **102** or client devices **108**. In some embodiments, the server **104** manages vehicle data **112** of each individual vehicle **102** separately. In some embodiments, the server **104** consolidates vehicle data **112** from multiple vehicles **102** and manages the consolidated vehicle data jointly (e.g., the server **104** statistically aggregates the data).

(23) Additionally, in some embodiments, the vehicle driving environment **100** further includes one or more client devices **108**, such as desktop computers, laptop computers, tablet computers, and mobile phones. Each client device **108** is configured to execute a client user application associated



with the central vehicle platform provided by the server **104**. The client device **108** is logged into a user account on the client user application, and the user account is associated with one or more vehicles **102**. The server **104** provides the collected vehicle data **112** and additional vehicle information **114** (e.g., vehicle operation information, fault information, or driving solution information) for the one or more associated vehicles **102** to the client device **108** using the user account of the client user application. In some embodiments, the client device **108** is located in the one or more vehicles **102**, while in other embodiments, the client device is at a location distinct from the one or more associated vehicles **102**. As such, the server **104** can apply its computational capability to manage the vehicle data **112** and facilitate vehicle monitoring and control on different levels (e.g., for each individual vehicle, for a collection of vehicles, and/or for related client devices **108**).

(24) The plurality of vehicles **102**, the one or more servers **104**, and the one or more client devices **108** are communicatively coupled to each other via one or more communication networks **110**, which is used to provide communications links between these vehicles and computers connected together within the vehicle driving environment **100**. The one or more communication networks **110** may include connections, such as a wired network, wireless communication links, or fiber optic cables. Examples of the one or more communication networks **110** include local area networks (LAN), wide area networks (WAN) such as the Internet, or a combination thereof. The one or more communication networks **110** are, in some embodiments, implemented using any known network protocol, including various wired or wireless protocols, such as Ethernet, Universal Serial Bus (USB), FIREWIRE, Long Term Evolution (LTE), Global System for Mobile Communications (GSM), Enhanced Data GSM Environment (EDGE), code division multiple access (CDMA), time division multiple access (TDMA), Bluetooth, Wi-Fi, voice over Internet Protocol (VOIP), Wi-MAX, or any other suitable communication protocol. A connection to the one or more communication networks **110** may be established either directly (e.g., using 3G/4G/5G connectivity to a wireless carrier), or through a network interface (e.g., a router, a switch, a gateway, a hub, or an intelligent, dedicated whole-home control node), or through any combination thereof. In some embodiments, the one or more communication networks **110** allow for communication using any suitable protocols, like Transmission Control Protocol/Internet Protocol (TCP/IP). In some embodiments, each vehicle **102** is communicatively coupled to the servers **104** via a cellular communication network.

(25) In some embodiments, deep learning techniques are applied by the vehicles **102**, the servers **104**, or both, to process the vehicle data **112**. For example, in some embodiments, after image data is collected by the cameras of one of the vehicles **102**, the image data is processed using an object detection model to identify objects (e.g., road features including, but not limited to, vehicles, lane lines, shoulder lines, road dividers, traffic lights, traffic signs, road signs, cones, pedestrians, bicycles, and drivers of the vehicles) in the vehicle driving environment **100**. In some embodiments, additional sensor data is collected and processed by a vehicle control model to generate a vehicle control instruction for controlling the vehicle control system. In some embodiments, a vehicle planning model is applied to plan a driving control process based on the collected sensor data and the vehicle driving environment **100**. The object detection model, vehicle control model, and vehicle planning model are collectively referred to herein as vehicle data processing models (i.e., machine learning models **250** in FIG. 2), each of which includes one or more neural networks. In some embodiments, such a vehicle data processing model is applied by the vehicles **102**, the servers **104**, or both, to process the vehicle data **112** to infer associated vehicle status and/or provide control signals. In some embodiments, a vehicle data processing model is trained by a server **104**, and applied locally or provided to one or more vehicles **102** for inference of the associated vehicle status and/or to provide control signals. Alternatively, a vehicle data processing model is trained locally by a vehicle **102**, and applied locally or shared with one or more other vehicles **102** (e.g., by way of the server **104**). In some embodiments, a vehicle data

processing model is trained in a supervised, semi-supervised, or unsupervised manner.

(26) In some embodiments, the vehicle driving environment **100** further includes one or more installations **130** (e.g., an infrastructure) that are situated along a road. For example, in some embodiments, the installations **130** can be positioned at locations along a road where traffic may be prone to buildup, such as a freeway entrance or exit, a lane merge zone (e.g., on a section of a road where two or more lanes merge), a tunnel, a toll booth, a traffic light area, an on-ramp region of a highway, and/or a junction (e.g., an intersection) where two or more roads converge, diverge, meet or cross. In some embodiments, a segment of a road can have multiple installations **130** that are positioned at regular intervals (e.g., every kilometer, every mile, every 2 miles, etc.) along the road. In some embodiments, the installations **130** comprise fixed, immovable structures. In some embodiments, the installations **130** are positioned ahead of traffic of interest (e.g., the vehicles are driving in a direction toward the installations).

(27) The one or more installations **130**, the plurality of vehicles **102**, the one or more servers **104**, and the one or more client devices **108** are communicatively coupled to each other via the one or more communication networks **110**. In some embodiments, a vehicle **102** can be equipped with a vehicle-to-infrastructure (V2I) communication system, in which the vehicle **102** and the one of more installations **130** are communicating nodes that provide each other with information such as traffic information, weather information, road condition information, and safety warnings. In accordance with some embodiments, V2I involves the exchange of information between vehicles **102** and components (e.g., sensors **660**, communication module **616**, data processing module **626**, and other components) of an installation **130**. In some embodiments, a respective vehicle **102** can be equipped with a vehicle-to-everything (V2X) communication system, in which the respective vehicle **102** can exchange information with the one of more installations **130** as well as with other vehicles that may be driving along the same road (e.g., route), or a different road, as the respective vehicle **102**. The V2I and/or V2X communication system can be powered using 3G/4G/5G connectivity to a wireless carrier, or through a network interface (e.g., a router, a switch, a gateway, a hub, or an intelligent, dedicated whole-home control node), or through any combination thereof. In some embodiments, the V2I or V2X communication are powered by 5G, which advantageously allows large bandwidth, low latency information sharing between the vehicles and the installations, providing new opportunities for road condition estimation and weather conditions perception.

(28) The installations **130** include one or more sensors **660** positioned at the installations **130**. The sensors **660** are fixedly located on the installations **130** and are configured to detect, monitor, and gather data on various traffic-related parameters (e.g., vehicle traffic data, including traffic density, an average vehicle speed, honking/beeping from vehicles). In accordance with some embodiments of the present disclosure, the information collected by the sensors **660** are more detailed and instantaneous compared to information collected using a perception system on a single autonomous vehicle, because they have a fixed location, better detection coverage, and a defined field of view. In some embodiments, the one or more sensors includes one or more of: an imaging sensor, a camera, a microphone (which may be part of the camera or separate from the camera), an anemometer (e.g., a wind speed and direction sensor), a global positioning system (GPS), a thermal sensor (e.g., a temperature sensor), an acoustic sensor, a microphone, a light detection and ranging (LiDAR) scanner, a radio detection and ranging (RADAR) sensor, an infrared sensor, an ultrasonic sensor. In some embodiments, the installations **130** include one or more inductive loop detectors for transmitting and receiving communication signals, and/or detecting the presence or vehicles.

(29) In some embodiments, a respective installation **130** includes a communication module for facilitating information sharing between the vehicles **102** and the installation **130**. For example, in some embodiments, the installation **130** gathers, from the vehicles **102** via the communication module, vehicle information **134**. The vehicle information **134** can include information about vehicle dynamics (e.g., vehicle velocities and accelerations), vehicle data **112**, and/or the additional vehicle information **114**. In some embodiments, the vehicle information **134** can also include

traffic, road, and/or weather information that are communicated from the vehicles **102** to the installation **130**.

(30) In some embodiments, the installation **130** provides at least a subset of infrastructure information **132** to the vehicles **102** and/or the one or more servers **104**. The infrastructure information **132** can include sensor data collected by the sensors **660** and/or data processed by a computing unit of the installation **130** based on the sensor data and the vehicle information **134**.

(31) It is noted that the installation **130** illustrated in FIG. **1** does not reflect an actual size of the installation **130**. In some embodiments, the installation **130** corresponds to an existing structure (e.g., a light pole, a billboard) standing near or on the road. Alternatively, in some embodiments, the installation **130** is a dedicated structure built at a fixed location near or on the road for collecting information of local road or weather conditions. The installation **130** may not be visible or discernable to passing vehicles from its appearance.

(32) FIG. **2** is a block diagram of an example vehicle **102** configured to be driven with a certain level of autonomy, in accordance with some embodiments. The vehicle **102** typically includes one or more processing units (CPUs) **202**, one or more network interfaces **204**, memory **206**, and one or more communication buses **208** for interconnecting these components (sometimes called a chipset). The vehicle **102** includes one or more user interface devices. The user interface devices include one or more input devices **210**, which facilitate user input, such as a keyboard, a mouse, a voice-command input unit or microphone, a touch screen display, a touch-sensitive input pad, a gesture capturing camera, or other input buttons or controls. Furthermore, in some embodiments, the vehicle **102** uses a microphone and voice recognition or a camera and gesture recognition to supplement or replace the keyboard. In some embodiments, the one or more input devices **210** include one or more cameras, scanners, or photo sensor units for capturing images, for example, of a driver and a passenger in the vehicle **102**. The vehicle **102** also includes one or more output devices **212**, which enable presentation of user interfaces and display content, including one or more speakers and/or one or more visual displays (e.g., a display panel located near to a driver's right hand in right-hand-side operated vehicles typical in the U.S.).

(33) The vehicle **102** includes a plurality of sensors **260** configured to collect sensor data in a vehicle driving environment **100**. The plurality of sensors **260** include one or more of a GPS **262**, a LiDAR scanner **264**, one or more cameras **266**, a RADAR sensor **268**, an infrared sensor **270**, one or more ultrasonic sensors **272**, an SRC module **274**, an INS **276** including accelerometers and gyroscopes, and an odometry sensor **278**. The GPS **262** localizes the vehicle **102** in Earth coordinates (e.g., using a latitude value and a longitude value) and can reach a first accuracy level less than 1 meter (e.g., 30 cm). The LiDAR scanner **264** uses light beams to estimate relative distances between the scanner **264** and a target object (e.g., another vehicle **102**), and can reach a second accuracy level better than the first accuracy level of the GPS **262**. The cameras **266** are installed at different locations on the vehicle **102** to monitor surroundings of the camera **266** from different perspectives. In some situations, a camera **266** is installed facing the interior of the vehicle **102** and configured to monitor the state of the driver of the vehicle **102**. The RADAR sensor **268** emits electromagnetic waves and collects reflected waves to determine the speed and a distance of an object over which the waves are reflected. The infrared sensor **270** identifies and tracks objects in an infrared domain when lighting conditions are poor. The one or more ultrasonic sensors **272** are used to detect objects at a short distance (e.g., to assist parking). The SRC module **274** is used to exchange information with a road feature (e.g., a traffic light). The INS **276** uses the accelerometers and gyroscopes to measure the position, the orientation, and the speed of the vehicle. The odometry sensor **278** tracks the distance the vehicle **102** has travelled, (e.g., based on a wheel speed). In some embodiments, based on the sensor data collected by the plurality of sensors **260**, the one or more processors **202** of the vehicle monitor its own vehicle state **282**, the driver or passenger state **284**, states of adjacent vehicles **286**, and road conditions **288** associated with a plurality of road features.

(34) The vehicle **102** has a control system **290**, including a steering control **292**, a braking control **294**, a throttle control **296**, a transmission control **298**, signaling and lighting controls, and other controls. In some embodiments, one or more actuators of the vehicle control system **290** are automatically controlled based on the sensor data collected by the plurality of sensors **260** (e.g., according to one or more of the vehicle state **282**, the driver or passenger state **284**, states of adjacent vehicles **286**, and/or road conditions **288**).

(35) The memory **206** includes high-speed random access memory, such as DRAM, SRAM, DDR RAM, or other random access solid state memory devices. In some embodiments, the memory includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. In some embodiments, the memory **206** includes one or more storage devices remotely located from one or more processing units **202**. The memory **206**, or alternatively the non-volatile the memory within the memory **206**, includes a non-transitory computer readable storage medium. In some embodiments, the memory **206**, or the non-transitory computer readable storage medium of the memory **206**, stores the following programs, modules, and data structures, or a subset or superset thereof: an operating system **214**, which includes procedures for handling various basic system services and for performing hardware dependent tasks; a network communication module **216**, which connects each vehicle **102** to other devices (e.g., another vehicle **102**, a server **104**, or a client device **108**) via one or more network interfaces (wired or wireless) and one or more communication networks **110**, such as the Internet, other wide area networks, local area networks, metropolitan area networks, and so on; a user interface module **218**, which enables presentation of information (e.g., a graphical user interface for an application **224**, widgets, websites and web pages thereof, audio content, and/or video content) at the vehicle **102** via one or more output devices **212** (e.g., displays or speakers); an input processing module **220**, which detects one or more user inputs or interactions from one of the one or more input devices **210** and interprets the detected input or interaction; a web browser module **222**, which navigates, requests (e.g., via HTTP), and displays websites and web pages thereof, including a web interface for logging into a user account of a user application **224** associated with the vehicle **102** or another vehicle; one or more user applications **224**, which are executed at the vehicle **102**. The user applications **224** include a vehicle user application that controls the vehicle **102** and enables users to edit and review settings and data associated with the vehicle **102**; a model training module **226**, which trains a machine learning model **250**. The model **250** includes at least one neural network and is applied to process vehicle data (e.g., sensor data and vehicle control data) of the vehicle **102**; a data processing module **228**, which performs a plurality of on-vehicle tasks, including, but not limited to, perception and object analysis **230**, vehicle localization and environment mapping **232**, vehicle drive control **234**, vehicle drive planning **236**, local operation monitoring **238**, and vehicle action and behavior prediction **240**; a vehicle database **242**, which stores vehicle data **112**, including: device settings **243**, including common device settings (e.g., service tier, device model, storage capacity, processing capabilities, communication capabilities, and/or medical procedure settings) of the vehicle **102**; user account information **244** for the one or more user applications **224** (e.g., user names, security questions, account history data, user preferences, and predefined account settings); network parameters **246** for the one or more communication networks **110**, (e.g., IP address, subnet mask, default gateway, DNS server, and host name); training data **248** for training the machine learning model **250**; machine learning models **250** for processing vehicle data **112**, where in some embodiments, the machine learning model **250** is applied to process one or more images captured by a first vehicle **102A** and predict a sequence of vehicle actions of a second vehicle through a hierarchy of interconnected vehicle actions; sensor data **254** captured or measured by the plurality of sensors **260**; mapping and location data **256**, which is determined from the sensor data **254** to map the vehicle driving environment **100** and locations of the vehicle **102** in the environment **100**; a hierarchy of interconnected vehicle actions **258** including a plurality of

predefined vehicle actions that are organized to define a plurality of vehicle action sequences; and vehicle control data **259**, which is automatically generated by the vehicle **102** or manually input by the user via the vehicle control system **290** based on predicted vehicle actions to drive the vehicle **102**.

(36) Each of the above identified elements may be stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing a function described above. The above identified modules or programs (i.e., sets of instructions) need not be implemented as separate software programs, procedures, modules or data structures, and thus various subsets of these modules may be combined or otherwise re-arranged in various embodiments. In some embodiments, the memory **206** stores a subset of the modules and data structures identified above. In some embodiments, the memory **206** stores additional modules and data structures not described above.

(37) FIG. **3** is a block diagram of a server **104** for monitoring and managing vehicles **102** in a vehicle driving environment (e.g., the environment **100** in FIG. **1**), in accordance with some embodiments. Examples of the server **104** include, but are not limited to, a server computer, a desktop computer, a laptop computer, a tablet computer, or a mobile phone. The server **104** typically includes one or more processing units (CPUs) **302**, one or more network interfaces **304**, memory **306**, and one or more communication buses **308** for interconnecting these components (sometimes called a chipset). The server **104** includes one or more user interface devices. The user interface devices include one or more input devices **310**, which facilitate user input, such as a keyboard, a mouse, a voice-command input unit or microphone, a touch screen display, a touch-sensitive input pad, a gesture capturing camera, or other input buttons or controls. Furthermore, in some embodiments, the server **104** uses a microphone and voice recognition or a camera and gesture recognition to supplement or replace the keyboard. In some embodiments, the one or more input devices **310** include one or more cameras, scanners, or photo sensor units for capturing images, for example, of graphic serial codes printed on electronic devices. The server **104** also includes one or more output devices **312**, which enable presentation of user interfaces and display content, including one or more speakers and/or one or more visual displays.

(38) The memory **306** includes high-speed random access memory, such as DRAM, SRAM, DDR RAM, or other random access solid state memory devices. In some embodiments, the memory includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. In some embodiments, the memory **306** includes one or more storage devices remotely located from one or more processing units **302**. The memory **306**, or alternatively the non-volatile memory within memory **306**, includes a non-transitory computer readable storage medium. In some embodiments, the memory **306**, or the non-transitory computer readable storage medium of the memory **306**, stores the following programs, modules, and data structures, or a subset or superset thereof: an operating system **314**, which includes procedures for handling various basic system services and for performing hardware dependent tasks; a network communication module **316**, which connects the server **104** to other devices (e.g., vehicles **102**, another server **104**, and/or client devices **108**) via one or more network interfaces (wired or wireless) and one or more communication networks **110**, such as the Internet, other wide area networks, local area networks, metropolitan area networks, and so on; a user interface module **318**, which enables presentation of information (e.g., a graphical user interface for user application **324**, widgets, websites and web pages thereof, audio content, and/or video content) at the vehicle **102** via one or more output devices **312** (e.g., displays or speakers); an input processing module **320**, which detects one or more user inputs or interactions from one of the one or more input devices **310** and interprets the detected input or interaction; a web browser module **322**, which navigates, requests (e.g., via HTTP), and displays websites and web pages thereof, including a web interface for logging into a user account of a user application **324**; one or more user applications **324**, which

are executed at the server **104**. The user applications **324** include a vehicle user application that associates vehicles **102** with user accounts and facilitates controlling the vehicles **102**, and enables users to edit and review settings and data associated with the vehicles **102**; a model training module **226**, which trains a machine learning model **250**, where the model **250** includes at least one neural network and is applied to process vehicle data (e.g., sensor data and vehicle control data) of one or more vehicles **102**; a data processing module **228**, which manages: a multi-vehicle operation monitoring platform **332** configured to collect vehicle data **112** from a plurality of vehicles **102**, monitor vehicle operation, detect faults, provide driving solutions, and update additional vehicle information **114** to individual vehicles **102** or client devices **108**. The data processing module **228** manages vehicle data **112** for each individual vehicle **102** separately or processes vehicle data **112** of multiple vehicles **102** jointly (e.g., statistically, in the aggregate); a multi-installation operation monitoring platform **334** configured to collect infrastructure information **132** from a plurality of installations **130**, monitor installation operation, detect faults (e.g., sensor **660** faults). In some embodiments, infrastructure information **132** for each individual installation **130** is managed separately. In some embodiments, infrastructure information **132** from multiple installations **130** are processed jointly (e.g., statistically, in the aggregate); and a scenario capturing system **700**, as described with respect to FIG. 7. The scenario capturing system **700** is configured to monitor vehicle traffic data based on sensors **660** from a plurality of installations **130** and automatically capture event data. In some embodiments, the event data is used offline for training autonomous vehicles to improve their decision making capabilities. In some embodiments, the event data is used for developing road agent models and traffic models in large scale autonomous vehicle platforms; one or more databases **340** for storing vehicle server data and infrastructure (e.g., installation) data, including: device settings **342**, which include common device settings (e.g., service tier, device model, storage capacity, processing capabilities, communication capabilities, and/or medical procedure settings) of the server **104**; user account information **344** for the one or more user applications **324** (e.g., user names, security questions, account history data, user preferences, and predefined account settings); network parameters **346** for the one or more communication networks **110**, (e.g., IP address, subnet mask, default gateway, DNS server, and host name); training data **248** for training the machine learning model **250**; machine learning models **250** for processing vehicle data; vehicle data **112**, which is collected from a plurality of vehicles **102** and includes sensor data **254**, mapping and location data **256**, and vehicle control data **259**; additional vehicle information **114**, including vehicle operation information, fault information, and/or driving solution information, which are generated from the collected vehicle data **112**; infrastructure information **132**, including data collected by sensors **660** of the installations **130** and data processed by the installations **130** based on the data collected by the sensors **660** and the vehicle information **134**; event recordings **350**, which includes data of events recorded using sensors **660** of installations **130**; event data **352**, which includes data generated from the event recordings **350**; historical traffic data **354**, which includes collections of event data **352**; and abstracted data **356**, which comprises event data that has been converted to a different data format. In some embodiments, the abstracted data **356** comprises a processed bird's-eye view (BEV) data format. In some embodiments, the abstracted data **356** comprises vectorized data with timestamps.

(39) Each of the above identified elements may be stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing a function described above. The above identified modules or programs (i.e., sets of instructions) need not be implemented as separate software programs, procedures, modules or data structures, and thus various subsets of these modules may be combined or otherwise re-arranged in various embodiments. In some embodiments, the memory **306** stores a subset of the modules and data structures identified above. In some embodiments, the memory **306** stores additional modules and data structures not described above.

(40) FIGS. 4, 5A, and 5B provide background on the machine learning systems described herein,

which are helpful in understanding the details of the embodiments described from FIG. 6 onward.

(41) FIG. 4 is a block diagram of a machine learning system **400** for training and applying machine learning models **250** for facilitating driving of a vehicle, in accordance with some embodiments. The machine learning system **400** includes a model training module **226** establishing one or more machine learning models **250** and a data processing module **228** for processing vehicle data **112** using the machine learning model **250**. In some embodiments, both the model training module **226** (e.g., the model training module **226** in FIG. 2) and the data processing module **228** are located within the vehicle **102**, while a training data source **404** provides training data **248** to the vehicle **102**. In some embodiments, the training data source **404** is the data obtained from the vehicle **102** itself, from a server **104**, from storage **106**, or from another vehicle or vehicles **102**. Alternatively, in some embodiments, the model training module **226** (e.g., the model training module **226** in FIG. 3) is located at a server **104**, and the data processing module **228** is located in a vehicle **102**. The server **104** trains the data processing models **250** and provides the trained models **250** to the vehicle **102** to process real-time vehicle data **112** detected by the vehicle **102**. In some embodiments, the training data **248** provided by the training data source **404** include a standard dataset (e.g., a set of road images) widely used by engineers in the autonomous vehicle industry to train machine learning models **250**. In some embodiments, the training data **248** includes vehicle data **112** and/or additional vehicle information **114**, which is collected from one or more vehicles **102** that will apply the machine learning models **250** or collected from distinct vehicles **102** that will not apply the machine learning models **250**. The vehicle data **112** further includes one or more of sensor data **254**, road mapping and location data **256**, and control data **259**. Further, in some embodiments, a subset of the training data **248** is modified to augment the training data **248**. The subset of modified training data is used in place of or jointly with the subset of training data **248** to train the machine learning models **250**.

(42) In some embodiments, the model training module **226** includes a model training engine **410**, and a loss control module **412**. Each machine learning model **250** is trained by the model training engine **410** to process corresponding vehicle data **112** to implement a respective on-vehicle task. The on-vehicle tasks include, but are not limited to, perception and object analysis **230**, vehicle localization and environment mapping **232**, vehicle drive control **234**, vehicle drive planning **236**, local operation monitoring **238**, and vehicle action and behavior prediction **240** (FIG. 2). Specifically, the model training engine **410** receives the training data **248** corresponding to a machine learning model **250** to be trained, and processes the training data to build the machine learning model **250**. In some embodiments, during this process, the loss control module **412** monitors a loss function comparing the output associated with the respective training data item to a ground truth of the respective training data item. In these embodiments, the model training engine **410** modifies the machine learning models **250** to reduce the loss, until the loss function satisfies a loss criteria (e.g., a comparison result of the loss function is minimized or reduced below a loss threshold). The machine learning models **250** are thereby trained and provided to the data processing module **228** of a vehicle **102** to process real-time vehicle data **112** from the vehicle.

(43) In some embodiments, the model training module **226** further includes a data pre-processing module **408** configured to pre-process the training data **248** before the training data **248** is used by the model training engine **410** to train a machine learning model **250**. For example, an image pre-processing module **408** is configured to format road images in the training data **248** into a predefined image format. For example, the preprocessing module **408** may normalize the road images to a fixed size, resolution, or contrast level. In another example, an image pre-processing module **408** extracts a region of interest (ROI) corresponding to a drivable area in each road image or separates content of the drivable area into a distinct image.

(44) In some embodiments, the model training module **226** uses supervised learning in which the training data **248** is labelled and includes a desired output for each training data item (also called the ground truth in some situations). In some embodiments, the desirable output is labelled

manually by people or labelled automatically by the model training module **226** before training. In some embodiments, the model training module **226** uses unsupervised learning in which the training data **248** is not labelled. The model training module **226** is configured to identify previously undetected patterns in the training data **248** without pre-existing labels and with little or no human supervision. Additionally, in some embodiments, the model training module **226** uses partially supervised learning in which the training data is partially labelled.

(45) In some embodiments, the data processing module **228** includes a data pre-processing module **414**, a model-based processing module **416**, and a data post-processing module **418**. The data pre-processing modules **414** pre-processes vehicle data **112** based on the type of the vehicle data **112**. In some embodiments, functions of the data pre-processing modules **414** are consistent with those of the pre-processing module **408**, and convert the vehicle data **112** into a predefined data format that is suitable for the inputs of the model-based processing module **416**. The model-based processing module **416** applies the trained machine learning model **250** provided by the model training module **226** to process the pre-processed vehicle data **112**. In some embodiments, the model-based processing module **416** also monitors an error indicator to determine whether the vehicle data **112** has been properly processed in the machine learning model **250**. In some embodiments, the processed vehicle data is further processed by the data post-processing module **418** to create a preferred format or to provide additional vehicle information **114** that can be derived from the processed vehicle data. The data processing module **228** uses the processed vehicle data to at least partially autonomously drive the vehicle **102** (e.g., at least partially autonomously). For example, the processed vehicle data includes vehicle control instructions that are used by the vehicle control system **290** to drive the vehicle **102**.

(46) In some embodiments, the data processing module **228** of the vehicle **102** (e.g., a first vehicle) is applied to perform perception and object analysis **230** by obtaining a road image including a road surface along which the first vehicle is travelling, identifying one or more identifiable objects on the road surface in the road image, and detecting a plurality of objects on the road surface in the road image. The data processing module **228** eliminates the one or more identifiable objects from the plurality of objects in the road image to determine one or more unidentifiable objects on the road surface in the road image. The first vehicle is at least partially autonomously driven by treating the one or more unidentifiable objects differently from the one or more identifiable objects. Further, in some embodiments, the machine learning models **250** of the vehicle **102** includes an object detection model **230A** and a drivable area model **230B**. The object detection model **230A** is configured to identify the one or more identifiable objects in the road image and associate each identifiable object with a predefined object type or class. The drivable area model **230B** is configured to determine a road surface in the road image. Additionally, in some embodiments, the machine learning models **250** includes a generic obstacle detection model **230C** configured to detect a plurality of objects on the road surface in the road image, e.g., with or without determining a predefined object type or class of each of the plurality of objects. The generic obstacle detection model **230C** is optionally modified from the drivable area model **230C** by way of retraining.

(47) FIG. 5A is a structural diagram of an example neural network **500** applied to process vehicle data in a machine learning model **250**, in accordance with some embodiments, and FIG. 5B is an example node **520** in the neural network **500**, in accordance with some embodiments. It should be noted that this description is used as an example only, and other types or configurations may be used to implement the embodiments described herein. The machine learning model **250** is established based on the neural network **500**. A corresponding model-based processing module **416** applies the machine learning model **250** including the neural network **500** to process vehicle data **112** that has been converted to a predefined data format. The neural network **500** includes a collection of nodes **520** that are connected by links **512**. Each node **520** receives one or more node inputs **522** and applies a propagation function **530** to generate a node output **524** from the one or more node inputs. As the node output **524** is provided via one or more links **512** to one or more



other nodes **520**, a weight  $w$  associated with each link **512** is applied to the node output **524**. Likewise, the one or more node inputs **522** are combined based on corresponding weights  $w_{sub.1}$ ,  $w_{sub.2}$ ,  $w_{sub.3}$ , and  $w_{sub.4}$  according to the propagation function **530**. In an example, the propagation function **530** is computed by applying a non-linear activation function **532** to a linear weighted combination **534** of the one or more node inputs **522**.

(48) The collection of nodes **520** is organized into layers in the neural network **500**. In general, the layers include an input layer **502** for receiving inputs, an output layer **506** for providing outputs, and one or more hidden layers **504** (e.g., layers **504A** and **504B**) between the input layer **502** and the output layer **506**. A deep neural network has more than one hidden layer **504** between the input layer **502** and the output layer **506**. In the neural network **500**, each layer is only connected with its immediately preceding and/or immediately following layer. In some embodiments, a layer is a “fully connected” layer because each node in the layer is connected to every node in its immediately following layer. In some embodiments, a hidden layer **504** includes two or more nodes that are connected to the same node in its immediately following layer for down sampling or pooling the two or more nodes. In particular, max pooling uses a maximum value of the two or more nodes in the layer for generating the node of the immediately following layer.

(49) In some embodiments, a convolutional neural network (CNN) is applied in a machine learning model **250** to process vehicle data (e.g., video and image data captured by cameras **266** of a vehicle **102**). The CNN employs convolution operations and belongs to a class of deep neural networks. The hidden layers **504** of the CNN include convolutional layers. Each node in a convolutional layer receives inputs from a receptive area associated with a previous layer (e.g., nine nodes). Each convolution layer uses a kernel to combine pixels in a respective area to generate outputs. For example, the kernel may be to a  $3 \times 3$  matrix including weights applied to combine the pixels in the respective area surrounding each pixel. Video or image data is pre-processed to a predefined video/image format corresponding to the inputs of the CNN. In some embodiments, the pre-processed video or image data is abstracted by the CNN layers to form a respective feature map. In this way, video and image data can be processed by the CNN for video and image recognition or object detection.

(50) In some embodiments, a recurrent neural network (RNN) is applied in the machine learning model **250** to process vehicle data **112**. Nodes in successive layers of the RNN follow a temporal sequence, such that the RNN exhibits a temporal dynamic behavior. In an example, each node **520** of the RNN has a time-varying real-valued activation. It is noted that in some embodiments, two or more types of vehicle data are processed by the data processing module **228**, and two or more types of neural networks (e.g., both a CNN and an RNN) are applied in the same machine learning model **250** to process the vehicle data jointly.

(51) The training process is a process for calibrating all of the weights  $w_{sub.i}$  for each layer of the neural network **500** using training data **248** that is provided in the input layer **502**. The training process typically includes two steps, forward propagation and backward propagation, which are repeated multiple times until a predefined convergence condition is satisfied. In the forward propagation, the set of weights for different layers are applied to the input data and intermediate results from the previous layers. In the backward propagation, a margin of error of the output (e.g., a loss function) is measured (e.g., by a loss control module **412**), and the weights are adjusted accordingly to decrease the error. The activation function **532** can be linear, rectified linear, sigmoidal, hyperbolic tangent, or other types. In some embodiments, a network bias term  $b$  is added to the sum of the weighted outputs **534** from the previous layer before the activation function **532** is applied. The network bias  $b$  provides a perturbation that helps the neural network **500** avoid over fitting the training data. In some embodiments, the result of the training includes a network bias parameter  $b$  for each layer.

(52) FIG. **6** is a block diagram of a computer system **600** associated with an installation **130** for detecting conditions for vehicle driving in a vehicle driving environment (e.g., the environment **100**

in FIG. 1), in accordance with some embodiments. The installation **130** includes a plurality of sensors **660**. In some embodiments, the plurality of sensors **660** include one or more of a GPS **662**, a LiDAR scanner **664**, one or more cameras **666**, a RADAR sensor **668**, one or more infrared sensor **670**, one or more ultrasonic sensors **672**, one or more thermal sensors **674** (e.g., for measuring heat and/or temperature), one or more anemometers **676** for measuring wind speed and wind direction, and one or more microphones **678** for capturing audio in a vicinity of the installation **130**. In some embodiments, the one or more microphones **678** are part of the cameras **666**. In some embodiments, the one or more microphones **678** are separate from the cameras **666**. In some embodiments, the plurality of sensors **660** include one or more inductive loop detectors **680** for transmitting and receiving communication signals, and/or detecting the presence or vehicles.

(53) In some embodiments, the computer system **600** is physically co-located at the installation **130**. For example, the computer system **600** comprises a microcontroller chip that is located locally at the installation **130**, and at least a subset of the data collected at the installation **130** (e.g., using the sensors **660**) is processed locally by the computer system **600**. In some embodiments, the computer system **600** is at a physical location different from the installation **130**. For example, the computer system **600** can comprise a cloud computer system that is communicatively connected to the installation **130**. In some embodiments, the computer system includes one or more distinct systems located at distinct locations of a road or distinct systems located at different roads. Examples of the computer system **600** include, but are not limited to, a server computer, a desktop computer, a laptop computer, a tablet computer, or a mobile phone. The computer system **600** typically includes one or more processing units (CPUs) **602**, one or more network interfaces **604**, memory **606**, and one or more communication buses **608** for interconnecting these components (sometimes called a chipset). The computer system **600** includes one or more user interface devices. The user interface devices include one or more input devices **610**, which facilitate user input, such as a keyboard, a mouse, a voice-command input unit or microphone, a touch screen display, a touch-sensitive input pad, a gesture capturing camera, or other input buttons or controls. Furthermore, in some embodiments, the computer system **600** uses a microphone and voice recognition or a camera and gesture recognition to supplement or replace the keyboard. In some embodiments, the one or more input devices **610** include one or more cameras, scanners, or photo sensor units for capturing images, for example, of graphic serial codes printed on electronic devices. The computer system **600** also includes one or more output devices **610**, which enable presentation of user interfaces and display content, including one or more speakers and/or one or more visual displays.

(54) The memory **606** includes high-speed random access memory, such as DRAM, SRAM, DDR RAM, or other random access solid state memory devices. In some embodiments, the memory includes non-volatile memory, such as one or more magnetic disk storage devices, one or more optical disk storage devices, one or more flash memory devices, or one or more other non-volatile solid state storage devices. In some embodiments, the memory **606** includes one or more storage devices remotely located from the one or more processing units **602**. The memory **606**, or alternatively the non-volatile memory within memory **606**, includes a non-transitory computer readable storage medium. In some embodiments, the memory **606**, or the non-transitory computer readable storage medium of the memory **606**, stores the following programs, modules, and data structures, or a subset or superset thereof: an operating system **614**, which includes procedures for handling various basic system services and for performing hardware dependent tasks; a communication module **616**, which connects the computer system to other devices (e.g., vehicles **102**, server **104**, installations **130**, and/or client devices **108**) via one or more network interfaces (wired or wireless) and one or more communication networks **110**, such as the Internet, other wide area networks, local area networks, metropolitan area networks, and so on. In some embodiments, the communications module **616** gathers information about road and weather conditions from

vehicles **102** via a V2I or a V2X communication system that is installed on the vehicles **102**. In some embodiments, the V2I or V2X communication system operate on a network that provides high speed, low latency communication; a user interface module **618**, which enables presentation of information, widgets, websites and web pages thereof, audio content, and/or video content) via one or more output devices **612** (e.g., displays or speakers); an input processing module **620**, which detects one or more user inputs or interactions from one of the one or more input devices **610** and interprets the detected input or interaction; a web browser module **622**, which navigates, requests (e.g., via HTTP), and displays websites and web pages thereof; a data processing module **626**, which: manages a multi-installation operation monitoring platform **334** configured to collect infrastructure information **132** from a plurality of installations **130**, monitor installation operation, detect faults (e.g., faults from sensors **660**). In some embodiments, the data processing module **626** manages infrastructure information **132** for each individual installation **130** separately or processes infrastructure information **132** from multiple installations **130** jointly (e.g., statistically, in the aggregate); and manages a scenario capturing system **700**, which is described with reference to FIG. 7; one or more machine learning models **628**. In some embodiments, the machine learning models **628** include at least one neural network and is applied to process vehicle traffic data collected by the sensors **660** and output a determination of whether the vehicle traffic data constitutes an event; data **630** that is stored locally on the computer system **600** or on one or more databases (e.g., database(s) **340**), including: infrastructure information **132**. In some embodiments, infrastructure information **132** includes data collected by sensors **660** of installations **130**. In some embodiments, infrastructure information **132** includes data that is processed by the installations **130** (e.g., via computer system **600**) according to data collected by sensors **660** and/or vehicle information **134**; vehicle information **134**. In some embodiments, vehicle information **134** includes information gathered by installations **130** from vehicles **102** via communication module **616**. In some embodiments, vehicle information **134** includes information about vehicle dynamics (e.g., vehicle velocities and accelerations), vehicle data **112**, and/or the additional vehicle information **114**. In some embodiments, the vehicle information **134** includes include traffic, road, and/or weather information that are transmitted from the vehicles **102** to the installations **130**; event recordings **350**, which includes data of events recorded using sensors **660** of installations **130**; event data **352**, which includes data generated from the event recordings **350**; historical traffic data **354**, which includes collections of event data **352**; and abstracted data **356**, which comprises event data that has been converted to a different data format. In some embodiments, the abstracted data **356** comprises a processed bird's-eye view (BEV) data format. In some embodiments, the abstracted data **356** comprises vectorized data with timestamps.

(55) Each of the above identified elements may be stored in one or more of the previously mentioned memory devices, and corresponds to a set of instructions for performing a function described above. The above identified modules or programs (i.e., sets of instructions) need not be implemented as separate software programs, procedures, modules or data structures, and thus various subsets of these modules may be combined or otherwise re-arranged in various embodiments. In some embodiments, the memory **606** stores a subset of the modules and data structures identified above. In some embodiments, the memory **606** stores additional modules and data structures not described above. In some embodiments, a subset of the operations performed at the computer system **600** can also be performed at the server **104**.

(56) FIG. 7 illustrates a scenario capturing system **700**, in accordance with some embodiments. In some embodiments, the scenario capturing system **700** enables continuous and low-cost generation of driving scenarios for training decision making algorithms on autonomous vehicles. In some embodiments, event data captured by the scenario capturing system **700** can be used for developing road agent models and traffic models in large scale autonomous vehicle driving platforms.

(57) In some embodiments, the scenario capturing system **700** includes an event detection module **702**, which is configured to monitor (e.g., continuously, periodically, or at regular intervals) vehicle

traffic data using the plurality of sensors **660** that are mounted on installations **130**. In some embodiments, the installations **130** are located in predefined zones of interest on a road, such as at a toll booth, an intersection, a freeway entrance or exit area, or a lane merge area.

(58) In accordance with some embodiments of the present disclosure, the scenario capturing system **700** does not capture (e.g., record) all of the monitored vehicle traffic data due to the large amounts of information involved. Instead, the scenario capturing system **700** triggers recording of only a subset (i.e., less than all) of the monitored vehicle traffic data when the event detection module **702** determines that the monitored vehicle traffic data qualifies as an “event.” As used herein, an event can be regarded as a situation that impacts the driving decision of an autonomous vehicle.

(59) In some embodiments, the event detection module **702** includes an anomaly detection unit **704** that executes a rule-based algorithm to determine whether an event has occurred. For example, in some embodiments, the anomaly detection unit **704** is configured to determine that an event has occurred when the vehicle traffic data satisfies one or more criteria, which can include: (i) a determination that the vehicle traffic in the zone of interest has unusually high traffic density or unusually low traffic speed (e.g., beyond 2 or 3 standard deviations of an average traffic density of the zone of interest, or beyond 2 or 3 standard deviations of an average vehicle speed of the zone of interest), (ii) a determination that a cumulative duration of the honk/beep within a fixed time window from one or multiple vehicles exceeds a certain threshold (e.g., 10 second threshold within a 30-second window), or (iii) a determination that the vehicle traffic is occurring at a predetermined time of the day or week, or particular season(s) in a year. In some embodiments, the event detection module **702** is configured to determine whether an event has occurred by comparing the vehicle traffic data against a set of predefined rules to determine whether the vehicle traffic data satisfies a rule of the set of predefined rules. The predefined rules can be based on the type(s) of vehicles that travel in the zone of interest of the road, or numbers of road users involved, or whether a collision is involved, or a severity of the collision.

(60) In some embodiments, the event detection module **702** includes data-driven detection unit **706** that implements a data-driven approach (e.g., non-rule based approach, an AI/ML approach) to determine whether an event has occurred. For example, the data-driven detection unit **706** may be configured to obtain the vehicle traffic data from the sensors **660**, and input at least a subset of the vehicle traffic data into a deep neural network (e.g., machine learning models **628**) that is configured to determine whether the vehicle traffic data satisfies one or more criteria for occurrence of the first event. In some embodiments, the neural network is trained to formulate/determine a “normal” traffic pattern for the location of the fixed installation by monitoring (e.g., continuously) the traffic data combined with other information such as the weather condition, a speed limit of a respective road, and whether or not extended roadwork(s) are present. In some circumstances, the “normal” traffic pattern can also depend on the time of a day, the day(s) of a week, or season(s) of a year. In some embodiments, the machine learning models **628** can be trained by labeled data generated from the rule-based approaches described with respect to the anomaly detection unit **704** above.

(61) In some embodiments, the event detection module **702** is configured to automatically trigger recording of an event, via the plurality of sensors **660**, when the anomaly detection unit **704** or the data-driven detection unit **706** determines that an event has occurred. In some embodiments, when an event recording is triggered, the scenario capturing system **700** (e.g., via the sensors **660**) records a set of signals related to traffic, weather, and road conditions for at least a predefined duration (e.g., 30 seconds).

(62) In some embodiments, the event detection module **702** temporarily stores road condition monitoring data in a rolling buffer with a pre-defined rolling buffer period (e.g., most recent 30 seconds, 60 seconds, or 90 seconds). When the recording of the event is triggered, the event detection module **702** adds at least a portion of the temporarily stored road condition monitoring data to the event recording.

(63) In some embodiments, the scenario capturing system **700** generates event data (e.g., event data **352**) based on recordings of one or more events (e.g., event recordings **350**) and adds the event data to a corpus of data to generate historical traffic data (e.g., historical traffic data **354**). In some embodiments, the event data (e.g., the historical traffic data) is used as training data to improve autonomous vehicle decision making modules.

(64) In some embodiments, the scenario capturing system **700** retains all the event recordings and generates event data based on all the event recordings. In some embodiments, the scenario capturing system **700** retains only a subset (i.e., less than all) of the event recordings by performing classification on the recorded events to identify scenarios (e.g., according to a complexity of an event).

(65) As depicted in FIG. 7, in some embodiments, the scenario capturing system **700** includes a scenario classification module **708** that is configured to classify the recorded events and determine a level of complexity of the events. In some embodiments, the scenario classification module **708** is configured to apply a vehicle behavior change index **710** to quantify event (e.g., scenario) complexity. For example, the vehicle behavior change index **710** can include a predetermined set of values (e.g., values “1”, “2”, and “3”). When a respective event involves a first vehicle, the scenario classification module **708** can select, from the predetermined set of values, a value corresponding to the behavior of the first vehicle in the respective event. For example, the scenario classification module **708** may assign the first vehicle in the respective event a value of “1” if the first vehicle changes its travel mode from cruising to hard braking, a value of “2” if it suddenly applies a braking action, or a value of “3” for the first index if it unexpectedly changes its lane at the same time that it suddenly applies its brakes. In some embodiments, the scenario classification module **708** is configured to quantify event (e.g., scenario) complexity according to a level-of-interest index **712**. Referring to the same example of the respective event involving the first vehicle, if the respective event also involves one or more other vehicles, the scenario classification module **708** can determine a respective value for each of these other vehicles using the vehicle behavior change index **710** and aggregate the values for the first vehicle and each of these other vehicles to derive an aggregated value corresponding to the level-of-interest index **712** (e.g., if the respective event involves just the first vehicle, the aggregate value corresponding to the level-of-interest index is the same as the value for the vehicle behavior change index for the first vehicle).

(66) In some embodiments, the scenario classification module **708** may compare the aggregated value against a threshold value. When the aggregated value satisfies (e.g., meets or exceeds) the threshold value, the scenario classification module **708** is configured to retain the recording and generate event data based on the recording. In some embodiments, the threshold value can be predefined according to a location of the fixed installation **130** (e.g., different locations can be assigned different threshold values). For example, a threshold value for recordings from toll booths may be lower than another threshold value for recordings from traffic junctions if toll booths are deemed to be of higher interest than traffic junctions, so as to ensure that the recordings from toll booths have a higher probability of being retained.

(67) In some embodiments, the scenario classification module **708** is configured to classify the recorded events and determine a level of complexity of the events according to the type(s) of vehicles involved, a number of road users involved, whether the event involves a collision between a vehicle and a human subject or between vehicles, or whether safety features such as the anti-lock braking system (ABS), electronic safety control (ESC), or Automatic emergency braking (AEB) features were triggered. For example, in some embodiments, the vehicles can communicate with the scenario capturing system **700** via the V2I communication system when safety features were triggered. In some embodiments, these details can be labeled (e.g., as tags) as event metadata to facilitate querying of the event data.

(68) In some embodiments, the scenario classification module **708** is configured to classify the recorded events and determine a level of complexity of the events according to an event type, or a

location where an event occurred. For example, the scenario classification module **708** can gather event recordings from various toll booths, aggregate all the toll booth event recordings, and transmit the data (e.g., via data transmission module **716**) to a backend server to facilitate the generation of a toll booth algorithm that enables autonomous vehicles navigate toll booths. A similar analogy applies to other event types/recordings, such as recordings from different freeway ramps, freeway exits, or traffic junctions.

(69) In some embodiments, the scenario classification module **708** is configured to combine the recorded events classification and the determined level of complexity information with other information such as the location of the installations **130** (e.g., whether it is at a toll booth, an intersection, etc.) to provide more detailed classification of the events.

(70) In some embodiments, the scenario capturing system **700** includes a data abstraction module **714** that is configured to reduce a data size of the event data and/or abstract information of users that may be involved in the events (e.g., because of privacy concern). For example, in some embodiments, the event data that is retained by the scenario classification module **708** may be encoded (e.g., as abstracted data **356**) in a way such that all vehicles are masked with new identifiers and only essential signals for reproducing the events are preserved. In some embodiments, the abstracted data **356** comprises a processed bird's-eye view (BEV) data format. In some embodiments, the abstracted data **356** comprises vectorized data with timestamps. In some embodiments, the event data (i.e., data prior to abstraction) is also stored locally and may be transferred to authorized institutions at a subsequent time.

(71) In some embodiments, the scenario capturing system **700** includes a data transmission module **716** that is configured to transmit the abstracted area and the event data. In some embodiments, when a first event involves a first vehicle, the data transmission module **716** is configured to receive data corresponding to the first event. In some embodiments, the data transmission module **716** is configured to transmit the event data and/or the abstracted data to a backend server for storage and/or further processing.

(72) FIGS. **8A** to **8C** provide a flowchart of an example process for automatic event capturing, in accordance with some embodiments. The method **800** is performed at a computer system (e.g., computer system **600**) that includes a plurality of sensors (e.g., sensors **660**) positioned on a fixed installation (e.g., installation **130**) at a road. In some embodiments, the plurality of sensors includes one or more cameras (e.g., cameras **666**) and one or more microphones (e.g., microphones **678**). The microphones **678** may be part of the cameras or separate from the cameras.

(73) In some embodiments, the computer system is physically co-located at the fixed installation and the processing is performed locally at the fixed installation. In some embodiments, the computer system is located remotely from and communicatively coupled to the fixed installation. In some embodiments, the computer system includes one or more (e.g., at least one or at least two) distinct systems located at distinct locations of the road. In one example, there may be multiple systems along the same road, each system including an installation having its own respective sensors **660** and/or processing capabilities. In another example, multiple systems may be located at different roads. For instance, a first system may be located at a on-ramp segment of a freeway and a second system may be located at a road junction; or a first system may be located at a toll booth in a first city and a second system may be located at another toll booth in a second city.

(74) The computer system includes one or more processors (e.g., CPU(s) **602**) and memory (e.g., memory **606**). In some embodiments, the memory stores one or more programs or instructions configured for execution by the one or more processors. In some embodiments, the operations shown in FIGS. **1**, **2**, **4**, **5A**, **5B**, **6**, and **7** correspond to instructions stored in the memory or other non-transitory computer-readable storage medium. The computer-readable storage medium may include a magnetic or optical disk storage device, solid state storage devices such as Flash memory, or other non-volatile memory device or devices. In some embodiments, the instructions stored on the computer-readable storage medium include one or more of: source code, assembly language

code, object code, or other instruction format that is interpreted by one or more processors. Some operations in the method **800** may be combined and/or the order of some operations may be changed.

(75) The computer system monitors (**802**) (e.g., continuously, periodically, or at regular intervals), using at least the plurality of sensors (e.g., sensors **660**) on the fixed installation (e.g., installation **130**), vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data (e.g., historical traffic data **354**). In some embodiments, a zone of interest of the road can include any segment of a road, an on-ramp region of a highway, a lane merge area of a highway, a road intersection, a toll booth, or a junction where two or more roads meet.

(76) In some embodiments, the computer system determines (**804**) (e.g., using event detection module **702**, based on the vehicle traffic data in a zone of interest of the road), whether a first event has occurred. As used herein, in some embodiments, an “event” can be regarded as a situation that impacts the driving decision of an autonomous vehicle.

(77) In some embodiments, the determination that the first event has occurred comprises rule-based determination (e.g., determined via anomaly detection unit **704**). For example, in some embodiments, the computer system determines that the first event has occurred when the vehicle traffic data satisfies (**806**) a first set of (e.g., one or more) criteria. In one example, the determination that the vehicle traffic satisfies the first set of criteria includes a determination that the vehicle traffic in the zone of interest has unusually high traffic density or unusually low traffic speed (e.g., beyond 2-3 standard deviations of an average traffic density of the zone of interest, or beyond 2-3 standard deviations of an average vehicle speed of the zone of interest. In another example, the determination that the vehicle traffic satisfies the first set of criteria includes a determination that a cumulative duration of the honk/beep within a fixed time window from one or more vehicles in the zone of interest of the road exceeds a certain threshold (e.g., 10 second threshold within a 30-sec window). In yet another example, the determination that the vehicle traffic satisfies the first set of criteria includes a determination that the vehicle traffic is occurring at a predetermined time of the day, or at a predefined time of the week, or at a particular season of the year. In some embodiments, a recording of the first event is triggered (e.g., automatically, without user intervention) when the threshold is satisfied or exceeded.

(78) In some embodiments, the determination that first event has occurred includes comparing (**808**) (e.g., using anomaly detection unit **704**) the vehicle traffic data against a set of predefined rules to determine whether the vehicle traffic data satisfies a rule of the set of (e.g., one or more) predefined rules. For example, the set of predefined rules can be based on the type(s) of vehicles that travel on the road, or the number of road users or vehicles involved, whether an accident (e.g., a collision) is involved, or the severity of the accident.

(79) In some embodiments, the determination that the first event has occurred comprises data-driven determination (e.g., determined using data-driven detection unit **706**). For example, in some embodiments, the computer system inputs (**810**) the vehicle traffic data into a deep neural network (e.g., machine learning models **628**) that is configured to determine whether the vehicle traffic data satisfies one or more criteria for occurrence of the first event. In some embodiments, the neural network is trained to formulate/determine a “normal” traffic pattern for the location of the fixed installation by monitoring (e.g., continuously) the traffic data combined with other information such as weather condition and/or whether extended roadwork(s) are present. The “normal” traffic pattern can also be dependent on time of the day, day of the week, and season of the year. In some embodiments, the machine learning models **628** can be trained by labeled data generated from the rule-based approaches as described above (e.g., whether the vehicle traffic in the zone of interest has unusually high traffic density or unusually low traffic speed (e.g., beyond 2-3 standard deviations of an average traffic density of the zone of interest, or beyond 2-3 standard deviations of an average vehicle speed of the zone of interest.), or whether a cumulative duration of the honk/beep within a fixed time window from one or multiple vehicles exceeds a certain threshold

(e.g., 10 second threshold within a 30-second window).

(80) In some embodiments, in accordance with a determination that the first event has occurred, the computer system triggers **(812)** (e.g., automatically, without user intervention) recording of the first event via the plurality of sensors (e.g., sensors **66**) (e.g., to obtain event recordings **350**), generates event data (e.g., event data **352**) based on the recording, and adds the event data to a corpus of data to generate the historical traffic data (e.g., historical traffic data **354**). In some embodiments, the triggering recording of the first event via the plurality of sensors occurs automatically and without user input.

(81) In some embodiments, the computer system temporarily stores **(814)** road condition monitoring data corresponding to a pre-defined buffer period such as the most recent 30 seconds, 60 seconds, or 90 seconds (e.g., as a rolling buffer). Triggering recording of the first event includes adding at least a portion of the temporarily stored road condition monitoring data to the first event recording.

(82) Referring to FIG. **8B**, in some embodiments, generating the event data based on the recording includes selecting **(816)** (e.g., via scenario classification module **708**), for a respective vehicle of one or more vehicles in the first event, a respective value from a predetermined set of values for a first index (e.g., vehicle behavior change index **710**) corresponding to a behavior of the respective vehicle in the first event. For example, in some embodiments, the predetermined set of values for the first index corresponding to the behavior of the respective vehicle in the first event comprises the values “1”, “2”, and “3”. The computer system may assign a value to a vehicle based on a list of vehicle behavior changes, depending on how drastic the behavior change of the vehicle is. A respective vehicle may be assigned a value of “1” for the first index if it changes from cruising to hard braking. The respective vehicle may be assigned a value of “2” for the first index if it suddenly applies a braking action. The respective vehicle may be assigned a value of “3” for the first index if the vehicle unexpectedly changes its lane at the same time that it suddenly applies a braking action.

(83) In some embodiments, generating the event data based on the recording includes determining **(818)** (e.g., via scenario classification module **708**), for the one or more vehicles in the first event, an aggregated value for a second index corresponding to a complexity of the first event. For example, the second index can be a level-of-interest index **712** that quantifies how complicated a scenario is (e.g., the more complex the scenario, the higher the level-of-interest index).

(84) In some embodiments, the computer system aggregates **(820)** one or more respective values for the first index, from the one or more vehicles in the first event, to obtain the aggregated value.

(85) In some embodiments, in accordance with a determination (e.g., by the computer system, via scenario classification module **708**) that the aggregated value satisfies a threshold value (e.g., the aggregated value is equal to, or exceeds, the threshold value), the computer system retains **(822)** the recording and generates the event data based on the recording. For example, in some embodiments, the threshold value can be designated according to a location of the fixed installation. As an example, a fixed installation that is located at a toll booth, a road junction/intersection, or at a merge zone may be of higher interest than another fixed installation that is located on a regular segment of a freeway. In some instances, a fixed installation that is located at a section of a road that is of higher interest may be designated a lower threshold value, to ensure that recordings from the higher interest locations have a higher probability of being retained.

(86) In some embodiments, the recording comprises **(824)** a first data format. Generating the event data based on the recording includes converting the recording having the first data format to the event data having a second data format (e.g., abstracted data **356**) that is different from the first data format. For example, the event data having the second data format can be of a different protocol or different data structure from the first data format, ensuring its correct interpretation upon receipt.

(87) In some embodiments, generating the event data based on the recording includes compressing



the recording having the first data format to the event data having the second data format the event data, such that the second data format has **(826)** a smaller file size than the recording having the first data format. For example, to reduce the data size to be transmitted and preserve the privacy of the road users, the computer system can encode the event data in a way that all vehicles in the first event are masked with new IDs and only essential signals for reproducing the event are preserved. (88) In some embodiments, the second data format comprises **(828)** a processed bird's-eye view (BEV) data format. In some instances, the BEV data format provides a convenient way to view the “larger picture” of the recording.

(89) In some embodiments, the recording having the second data format comprises **(830)** vectorized data with timestamps.

(90) With continued reference to FIG. **8C**, in some embodiments, the computer system records **(832)** the first event for at least a predefined time duration (e.g., 20 seconds, 30 seconds, or one minute).

(91) In some embodiments, the computer system stores **(834)** the recording of the first event. For example, in some embodiments, the recording of the first event is raw data of the first event. In some embodiments, the recording is stored locally on the computer system, or remotely on a database that is communicatively connected with the computer system. In some instances, the recording of the first event can be transferred to authorized institutions. For example, if the recording of the first event captures a traffic accident, a portion of the recording may be transmitted to authorized institutions such as a Highway Patrol unit.

(92) In some embodiments, the first event involves **(835)** a first vehicle. The method includes transmitting (e.g., via data transmission module **716**) the recording of the first event to the first vehicle. For example, the transmitting can be in response to receiving a request from the first vehicle to receive the event data.

(93) In some embodiments, the computer system facilitates **(836)** (e.g., enables or causes) labeling of the event data. For example, a human, the computer system, or another computing device can add tags to an event for easier querying. The tags can include a location at which the data is recorded (e.g., toll booth, intersection region, merger zone), whether collision is involved, and whether vehicle safety features such as an anti-lock braking system (ABS), an automatic emergency braking (AEB) system, or lean electronic stability control (ESC) system were triggered.

(94) In some embodiments, the computer system receives **(838)** vehicle operational data from one or more vehicles (e.g., via a wireless communication network such as a 5G network, or via a V2I or V2X communication system of the one or more vehicles) that are traveling in the zone of interest of the road over the period of time. The computer system uses the vehicle operational data to generate the historical traffic data (e.g., historical traffic data **354**). For example, in some embodiments, the vehicle traffic data includes vehicle operational data/conditions of one or more vehicles traveling in the zone of interest, such as whether safety features such as the anti-lock braking system (ABS), electronic safety control (ESC), or Automatic emergency braking (AEB) features, were triggered.

(95) The computer system uses **(840)** the historical traffic data to train (e.g., at least partially train) a driving model of an at least partially autonomous vehicle. In some embodiments, the training is performed offline (e.g., not real time), asynchronously with the recording or scenario classification. In some embodiments, the training is performed in real time, synchronously with the recording or scenario classification.

(96) The computer system sends **(842)** the driving model to one or more vehicles. The driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a similar zone of interest.

(97) Turning on to some example embodiments: (A1) In accordance with some embodiments, a method for automatic event capturing is performed at a computer system that includes a plurality of sensors that are positioned on a fixed installation at a road, one or more processors, and memory.

The method includes: (i) monitoring, by the plurality of sensors on the fixed installation, vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data; (ii) using the historical traffic data to train a driving model of an at least partially autonomous vehicle; and (iii) sending the driving model to one or more vehicles, where the driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a similar zone of interest. (A2) In some embodiments of A1, the computer system includes one or more distinct systems located at distinct locations of the road. (A3) In some embodiments of A1 or A2, monitoring the vehicle traffic data in the zone of interest of the road includes, in accordance with a determination that a first event has occurred: (i) triggering recording of the first event via the plurality of sensors; (ii) generating event data based on the recording; and (iii) adding the event data to a corpus of data to generate the historical traffic data. (A4) In some embodiments of A3, the method further includes temporarily storing road condition monitoring data corresponding to a pre-defined buffer period. Triggering recording of the first event includes adding at least a portion of the temporarily stored road condition monitoring data to the first event recording. (A5) In some embodiments of A3 or A4, determining that the first event has occurred includes determining that the vehicle traffic data satisfies a first set of criteria. (A6) In some embodiments of any of A3-A5, the determination that first event has occurred includes comparing the vehicle traffic data against a set of predefined rules to determine whether the vehicle traffic data satisfies a rule of the set of predefined rules. (A7) In some embodiments of any of A3-A6, the determination that that first event has occurred includes inputting the vehicle traffic data into a deep neural network that is configured to determine whether the vehicle traffic data satisfies one or more criteria for occurrence of the first event. (A8) In some embodiments of any of A3-A7, generating the event data based on the recording includes selecting, for a respective vehicle of one or more vehicles in the first event, a respective value from a predetermined set of values for a first index corresponding to a behavior of the respective vehicle in the first event. (A9) In some embodiments of A8, generating the event data based on the recording includes determining, for the one or more vehicles in the first event, an aggregated value for a second index corresponding to a complexity of the first event. (A10) In some embodiments of A9, determining the aggregated value includes aggregating one or more respective values for the first index, from the one or more vehicles in the first event, to obtain the aggregated value. (A11) In some embodiments of A9 or A10, the method further includes, in accordance with a determination that the aggregated value satisfies a threshold value: (i) retaining the recording; and (ii) generating the event data based on the recording. (A12) In some embodiments of any of A3-A11, the recording comprises a first data format. Generating the event data based on the recording includes converting the recording having the first data format to the event data having a second data format that is different from the first data format. (A13) In some embodiments of A12, the event data having the second data format has a smaller file size than the recording having the first data format. (A14) In some embodiments of A12 or A13, the second data format comprises a processed bird's-eye view (BEV) data format. (A15) In some embodiments of any of A12-A14, the recording having the second data format comprises vectorized data with timestamps. (A16) In some embodiments of any of A3-A15, the method further includes recording the first event for at least a predefined time duration. (A17) In some embodiments of any of A3-A16, the method further includes storing the recording of the first event. (A18) In some embodiments of any of A3-A17, the first event involves a first vehicle. The method further includes transmitting the recording of the first event to the first vehicle. (A19) In some embodiments of any of A3-A18, the method further includes facilitating labeling of the event data. (A20) In some embodiments of any of A1-A19, the method further includes: receiving vehicle operational data from one or more vehicles that are traveling in the zone of interest of the road over the period of time; and using the vehicle operational data to generate the historical traffic data. (A21) In some embodiments of any of A1-A20, the plurality of sensors include: one or more cameras; and one or more microphones. (B1) In accordance with some

embodiments, a computer system is associated with a fixed installation having a plurality of sensors. The computer system comprises one or more processors and memory coupled to the one or more processors. The memory stores instructions that, when executed by the one or more processors, cause the computer system to perform the method of any of A1-A21. (C1) In accordance with some embodiments, a non-transitory computer-readable storage medium stores instructions that, when executed by one or more processors of computer system that is associated with a fixed installation having a plurality of sensors, cause the computer system to perform the method of any of A1-A21.

(98) As used herein, the term “plurality” denotes two or more. For example, a plurality of components indicates two or more components. The term “determining” encompasses a wide variety of actions and, therefore, “determining” can include calculating, computing, processing, deriving, investigating, looking up (e.g., looking up in a table, a database or another data structure), ascertaining and the like. Also, “determining” can include receiving (e.g., receiving information), accessing (e.g., accessing data in a memory) and the like. Also, “determining” can include resolving, selecting, choosing, establishing and the like.

(99) As used herein, the phrase “based on” does not mean “based only on,” unless expressly specified otherwise. In other words, the phrase “based on” describes both “based only on” and “based at least on.”

(100) As used herein, the term “exemplary” means “serving as an example, instance, or illustration,” and does not necessarily indicate any preference or superiority of the example over any other configurations or implementations.

(101) As used herein, the term “and/or” encompasses any combination of listed elements. For example, “A, B, and/or C” includes the following sets of elements: A only, B only, C only, A and B without C, A and C without B, B and C without A, and a combination of all three elements, A, B, and C.

(102) The terminology used in the description of the invention herein is for the purpose of describing particular implementations only and is not intended to be limiting of the invention. As used in the description of the invention and the appended claims, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will also be understood that the term “and/or” as used herein refers to and encompasses any and all possible combinations of one or more of the associated listed items. It will be further understood that the terms “comprises” and/or “comprising,” when used in this specification, specify the presence of stated features, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, steps, operations, elements, components, and/or groups thereof.

(103) The foregoing description, for purpose of explanation, has been described with reference to specific implementations. However, the illustrative discussions above are not intended to be exhaustive or to limit the invention to the precise forms disclosed. Many modifications and variations are possible in view of the above teachings. The implementations were chosen and described in order to best explain the principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various implementations with various modifications as are suited to the particular use contemplated.

## Claims

1. A method for automatic event capturing, comprising: at a computer system that includes a plurality of sensors that are positioned on a fixed installation at a road, one or more processors, and memory: monitoring, by the plurality of sensors on the fixed installation, vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data, wherein the zone of interest is of a first type; using the historical traffic data to train a driving model of an at

least partially autonomous vehicle; and sending the driving model to one or more vehicles, wherein the driving model is configured to be used by the one or more vehicles to at least partially autonomously drive along a first trajectory while the one or more vehicles are traveling through a zone of the first type and wherein the driving model supplements an existing vehicle control system that is controlling the one or more vehicles and is only used while the one or more vehicles are traveling through the zone of the first type.

2. The method of claim 1, wherein monitoring the vehicle traffic data in the zone of interest of the road includes: in accordance with a determination that a first event has occurred: triggering a recording of the first event via the plurality of sensors; and generating event data based on the recording; and adding the event data to a corpus of data to generate the historical traffic data.

3. The method of claim 2, further comprising: temporarily storing road condition monitoring data corresponding to a pre-defined buffer period; and wherein triggering the recording of the first event includes adding at least a portion of the temporarily stored road condition monitoring data to the recording of the first event.

4. The method of claim 2, wherein determining that the first event has occurred includes determining that the vehicle traffic data satisfies a first set of criteria.

5. The method of claim 2, wherein the determination that first event has occurred includes: comparing the vehicle traffic data against a set of predefined rules to determine whether the vehicle traffic data satisfies a rule of the set of predefined rules.

6. The method of claim 2, wherein the determination that the first event has occurred includes: inputting the vehicle traffic data into a deep neural network that is configured to determine whether the vehicle traffic data satisfies one or more criteria for occurrence of the first event.

7. The method of claim 2, wherein generating the event data based on the recording includes: selecting, for a respective vehicle of one or more vehicles in the first event, a respective value from a predetermined set of values for a first index corresponding to a behavior of the respective vehicle in the first event.

8. The method of claim 7, wherein generating the event data based on the recording includes: determining, for the one or more vehicles in the first event, an aggregated value for a second index corresponding to a complexity of the first event.

9. The method of claim 8, wherein determining the aggregated value includes: aggregating one or more respective values for the first index, from the one or more vehicles in the first event, to obtain the aggregated value.

10. The method of claim 8, further comprising: in accordance with a determination that the aggregated value satisfies a threshold value: retaining the recording; and generating the event data based on the recording.

11. The method of claim 2, wherein: the recording comprises a first data format; and generating the event data based on the recording includes converting the recording having the first data format to the event data having a second data format that is different from the first data format.

12. The method of claim 11, wherein the event data having the second data format has a smaller file size than the recording having the first data format.

13. The method of claim 11, wherein the second data format comprises a processed bird's-eye view (BEV) data format.

14. The method of claim 11, wherein the recording having the second data format comprises vectorized data with timestamps.

15. The method of claim 2, wherein the recording of the first event is recorded for at least a predefined time duration.

16. The method of claim 2, wherein: the first event involves a first vehicle; and the method further includes transmitting the recording of the first event to the first vehicle.

17. A computer system for automatic event capturing, comprising: a plurality of sensors that are positioned on a fixed installation at a road; one or more processors; and memory coupled to the one

or more processors, the memory storing one or more programs configured for execution by the one or more processors, the one or more programs including instructions for: monitoring, by the plurality of sensors on the fixed installation, vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data, wherein the zone of interest is of a first type; using the historical traffic data to train a driving model of an at least partially autonomous vehicle; and sending the driving model to one or more vehicles, wherein the driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a zone of the first type and wherein the driving model supplements an existing vehicle control system that is controlling the one or more vehicles and is only used while the one or more vehicles are traveling through the zone of the first type.

18. The computer system of claim 17, wherein the computer system includes one or more distinct systems located at distinct locations of the road.

19. A non-transitory computer-readable storage medium storing one or more programs configured for execution by one or more processors of a computer system that includes a plurality of sensors that are positioned on a fixed installation at a road, one or more processors, and memory, the one or more programs comprising instructions for: monitoring, by the plurality of sensors on the fixed installation, vehicle traffic data in a zone of interest of the road over a period of time to generate historical traffic data, wherein the zone of interest is of a first type; using the historical traffic data to train a driving model of an at least partially autonomous vehicle; and sending the driving model to one or more vehicles, wherein the driving model is configured to be used by the one or more vehicles to at least partially autonomously drive in a first trajectory while the one or more vehicles are traveling through a zone of the first type and wherein the driving model supplements an existing vehicle control system that is controlling the one or more vehicles and is only used while the one or more vehicles are traveling through the zone of the first type.

20. The non-transitory computer-readable storage medium of claim 19, the one or more programs further comprising instructions for: receiving vehicle operational data from one or more vehicles that are traveling in the zone of interest of the road over the period of time; and using the vehicle operational data to generate the historical traffic data.

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