

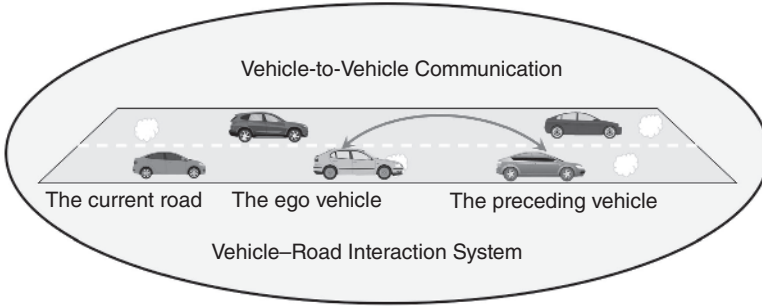
# 1

## Introduction

### 1.1 The Definition of Vehicle–Road Interaction System

Traffic accidents are one of the main causes of human casualties [1]. Intelligent connected vehicles will provide a new possibility for the automotive industry to effectively solve safety and congestion problems due to their functions of intelligent decision-making and collaborative control. Some typical technologies include vehicle road coordination systems, advanced driver assistance systems (ADAS), etc. Some of the most representative technologies in ADAS include stability control systems [2, 3], braking control systems [4–7], local path planning systems [8, 9], active suspension control systems [10–12], etc. The prerequisite for these active safety systems to work effectively is to obtain accurate vehicle state and tire-road friction coefficient (TRFC) [1]. To describe these vehicle states and road surface information in a unified way, this book adopts the concept of “interaction system” and defines the set composed of the host vehicle, the preceding vehicle, and the current road as the vehicle–road interaction system. As shown in Fig. 1.1, the corresponding variables, such as vehicle sideslip angle, tire stiffness, and TRFC, constitute the key state parameters in the vehicle–road interaction system. However, onboard sensors fail to directly obtain this information. Therefore, estimating these states using only onboard sensors is a hot topic of current research.

In the context of vehicle-to-vehicle (V2V) communication, the host vehicle, the preceding vehicle, and the road form a multi-agent vehicle–road interaction system due to their dynamic interdependence and interactive roles. The host vehicle acts as an independent agent, constantly interacting with its environment by adjusting its control actions based on its own dynamic states and real-time information from the preceding vehicle and road conditions. The preceding vehicle, another independent agent, influences the host vehicle’s behavior through its speed, acceleration, and position, impacting car-following decisions and safety measures. Additionally, the road, though not a vehicle, can be viewed as an agent due to its influence on vehicle dynamics via tire–road interactions,



**Figure 1.1** The vehicle–road interaction system.

such as road friction and surface conditions, which directly affect vehicle stability and performance. These three components—host vehicle, preceding vehicle, and road—communicate and interact within a shared environment, forming a tightly coupled multi-agent system. This framework allows for more accurate state estimation and decision-making, which is essential for the development of ADAS and autonomous driving technologies. In previous studies, host vehicle and preceding vehicle state estimation, as well as TRFC identification, are usually considered as two types of parameter identification problems. However, in this book, we try to define a new concept to describe a more macroscopic vehicle–road coupled system. This will provide a new perspective to researchers in this field. Therefore, these different states, or TRFC, will become the internal states of this macroscopic system.

## 1.2 The Importance of State Estimation for Vehicle–Road Interaction System

State estimation plays a crucial role in the development of vehicle–road interaction systems, directly impacting the safety, efficiency, and reliability of vehicles. This technology is fundamental for the operation of autonomous vehicles, as it allows for accurate sensing and understanding of both the vehicle’s state and its surrounding environment. By doing so, state estimation enables intelligent vehicles to make autonomous decisions and execute complex driving maneuvers. Accurate state estimation supports ADAS such as adaptive cruise control (ACC), lane-keeping assist, and emergency braking. For ACC, state estimation helps maintain a safe distance from the vehicle ahead by continuously monitoring relative speed and distance. Lane-keeping assist relies on state estimation to ensure the vehicle stays centered in its lane by detecting lane markings and making necessary steering adjustments. Emergency braking systems use state estimation to detect potential

collisions and apply brakes in time to avoid or mitigate the impact. Furthermore, state estimation enhances the efficiency and reliability of autonomous vehicles. By optimizing driving patterns based on accurate state information, vehicles can achieve smoother acceleration and braking, better fuel economy, and reduced emissions. Reliable state estimation ensures that autonomous vehicles can operate consistently in various conditions, from clear weather to rain or snow, thus building trust in autonomous vehicle technology. In summary, vehicle state estimation is a cornerstone of autonomous vehicle technology. It integrates sensor data, mathematical models, and advanced algorithms to provide a comprehensive understanding of a vehicle's dynamics and its immediate environment. This enables intelligent vehicles to make informed, autonomous decisions, ultimately improving the safety, efficiency, and reliability of modern transportation systems.

Vehicle state estimation involves the real-time determination of a vehicle's yaw rate, sideslip angle, velocity, and other pertinent parameters. These parameters are critical for assessing the vehicle's current status and predicting its future behavior, which is essential for facilitating safe and effective decision-making in autonomous vehicles.

The yaw rate of a vehicle, representing its rotational motion around the vertical axis, holds a central position in the realm of vehicle dynamics. It directly impacts the vehicle's stability during maneuvers such as turns and lane changes. A controlled and well-monitored yaw rate is critical for preventing oversteer or understeer conditions, both of which can lead to loss of control and compromise safety. In the context of vehicle dynamics, yaw rate plays a pivotal role in ensuring the vehicle's stability and responsiveness. During a turn, the yaw rate determines how quickly the vehicle rotates about its vertical axis. If the yaw rate is too high, it can result in oversteer, where the rear wheels lose traction and the vehicle turns more sharply than intended. Conversely, if the yaw rate is too low, it can lead to understeer, where the front wheels lose traction, causing the vehicle to turn less sharply than the driver intends. Both conditions can be dangerous, especially at high speeds or on slippery surfaces. By precisely managing the yaw rate, vehicles can navigate corners with optimal stability, reducing the risk of skidding or rollovers. This is achieved through advanced control systems such as electronic stability control (ESC), which continuously monitors the yaw rate and other parameters to make real-time adjustments. ESC systems apply brake force to individual wheels and adjust engine power to correct oversteer or understeer, helping the driver maintain control of the vehicle. The importance of yaw rate control becomes even more evident in emergency situations. Rapid changes in direction, such as during evasive maneuvers to avoid an obstacle, demand judicious control of the yaw rate to ensure the vehicle's response aligns with the driver's intentions. In such scenarios, the ability to swiftly and accurately adjust the yaw rate can make the difference between avoiding a collision and losing control. For instance,

consider a situation where a driver must swerve to avoid a sudden obstacle on the road. The vehicle's stability control system, relying on yaw rate sensors, will detect the rapid change in direction and intervene to maintain stability. By modulating brake pressure on individual wheels and adjusting throttle input, the system helps the vehicle follow the desired path while preventing oversteer or understeer. This intervention occurs in a matter of milliseconds, often faster than a human driver can react, thereby enhancing safety. Moreover, maintaining an optimal yaw rate is crucial for ensuring passenger comfort. Sudden or excessive rotational movements can be unsettling for passengers, leading to discomfort and motion sickness. By managing the yaw rate effectively, the vehicle can provide a smoother ride, enhancing overall comfort and driving experience. In the realm of autonomous driving, yaw rate control is even more critical. Autonomous vehicles rely on precise control of all dynamic parameters, including yaw rate, to execute complex maneuvers safely and efficiently. Advanced algorithms and sensor fusion techniques are employed to continuously monitor and adjust the yaw rate, ensuring the vehicle remains stable and responsive under all conditions.

In conclusion, the yaw rate of a vehicle is a fundamental aspect of vehicle dynamics, and is crucial for maintaining stability and safety during various driving maneuvers. Whether it is preventing oversteer and understeer in everyday driving or ensuring precise control during emergency situations, effective yaw rate management is essential. Advanced stability control systems and autonomous driving technologies rely heavily on yaw rate data to enhance vehicle performance and passenger safety, underscoring its significance in modern automotive engineering.

The sideslip angle, indicating the angle between a vehicle's velocity vector and its heading angle, is a fundamental parameter influencing lateral stability. A controlled sideslip angle is integral to preventing uncontrollable skidding and maintaining the vehicle's trajectory during dynamic maneuvers. This parameter is critical for ensuring that the vehicle responds predictably to driver inputs, particularly during high-speed driving, abrupt steering inputs, or when navigating adverse road conditions. In the context of vehicle dynamics, the sideslip angle plays a pivotal role in maintaining the vehicle's stability. When a vehicle is in motion, its tires generate lateral forces to counteract any sideways motion. The sideslip angle quantifies the deviation between the vehicle's intended path and its actual path. If this angle becomes too large, it indicates that the tires are losing grip on the road surface, which can lead to a loss of control and potential skidding. Therefore, managing the sideslip angle is crucial for maintaining the vehicle's lateral stability and ensuring safe handling characteristics. Excessive sideslip angles can lead to loss of tire grip, compromising the vehicle's ability to respond predictably to driver commands. For instance, during a sharp turn or a sudden evasive maneuver, the sideslip angle increases as the lateral forces acting on the tires intensify. If the tires exceed their grip limit, they will start to slide

sideways, resulting in a loss of control. This situation is particularly dangerous on slippery or uneven road surfaces, where the risk of skidding is higher. By controlling the sideslip angle, vehicles can maintain optimal tire grip, ensuring stable and predictable handling.

Advanced control systems play a crucial role in managing the sideslip angle to enhance vehicle safety. Modern vehicles are equipped with sophisticated systems such as ESC and traction control systems (TCS) that continuously monitor and adjust the sideslip angle. These systems use sensors to measure the vehicle's speed, steering angle, and yaw rate, among other parameters. By analyzing this data in real time, they can detect any deviation from the intended path and apply corrective measures. For example, if the ESC system detects that the sideslip angle is increasing beyond safe limits during a turn, it can selectively apply brake force to individual wheels and adjust engine power to counteract the sideways motion. This helps to bring the vehicle back on its intended trajectory, reducing the risk of skidding and enhancing overall stability. Similarly, the TCS system can modulate the power delivery to the wheels to prevent excessive wheel spin and maintain optimal traction, especially on slippery surfaces. The importance of controlling the sideslip angle is particularly evident in emergency situations. During sudden maneuvers to avoid obstacles or navigate sharp curves, the sideslip angle can change rapidly. Advanced control systems must react swiftly to these changes to maintain vehicle stability. By keeping the sideslip angle within stable operational limits, these systems enhance the vehicle's ability to respond effectively to driver commands, ensuring a safer driving experience. In autonomous vehicles, the management of the sideslip angle is even more critical. Autonomous driving algorithms rely on precise control of all vehicle dynamics to execute complex maneuvers safely. These algorithms use advanced sensor fusion techniques and predictive models to monitor and adjust the sideslip angle continuously. This ensures that the autonomous vehicle can navigate through various driving conditions with optimal stability and safety.

In conclusion, the sideslip angle is a vital parameter influencing the lateral stability of a vehicle. Effective management of the sideslip angle is essential to prevent uncontrollable skidding, maintain the vehicle's trajectory, and ensure predictable handling. Advanced control systems such as ESC and TCS are crucial in continuously monitoring and adjusting the sideslip angle to enhance vehicle safety. By maintaining stable operational limits, these systems contribute significantly to overall road safety, providing a safer and more reliable driving experience.

Longitudinal velocity, representing the rate of change of a vehicle's position along its direction of motion, and lateral velocity, depicting the rate of change of position perpendicular to the direction of motion, collectively play pivotal roles in determining a vehicle's stability, maneuverability, and response to various driving conditions. These two components of velocity are integral to understanding and managing a vehicle's dynamics. Longitudinal velocity, often associated

with acceleration and deceleration, directly affects a vehicle's dynamics and braking performance. In emergency braking situations, the ability to modulate longitudinal velocity is crucial for avoiding collisions and ensuring the safety of occupants and pedestrians. Advanced antilock braking systems (ABS) and ESC mechanisms leverage longitudinal velocity data to optimize braking forces, preventing wheel lockup and skidding. ABS prevents the wheels from locking up during hard braking, allowing the driver to maintain steering control. ESC, on the other hand, helps to maintain vehicle stability by detecting and reducing the loss of traction. By continuously monitoring longitudinal velocity, these systems can adjust braking force distribution to ensure maximum efficiency and safety. Longitudinal velocity is also integral to the operation of ACC systems. ACC systems maintain a set following distance from the vehicle ahead by adjusting the throttle and brake based on longitudinal velocity. This enhances safety by providing a seamless response to changes in traffic conditions, reducing the risk of rear-end collisions. The ACC system uses sensors to monitor the speed and distance of the vehicle in front, adjusting the vehicle's speed accordingly. This not only ensures a safer driving experience but also enhances comfort by reducing the need for manual speed adjustments in varying traffic conditions. Moreover, collision avoidance systems utilize longitudinal velocity information to assess the risk of an impending collision and initiate pre-crash measures, such as autonomous emergency braking (AEB). AEB systems are designed to detect potential collisions and automatically apply the brakes if the driver does not respond in time. By analyzing longitudinal velocity along with other parameters like the distance to the obstacle and the relative speed, these systems can determine the likelihood of a collision and take preventive action. This significantly reduces the chances of accidents, protecting both the vehicle's occupants and other road users.

Lateral velocity, while less commonly discussed, is equally important for vehicle stability and maneuverability. Lateral velocity affects how the vehicle responds to steering inputs and how well it can maintain its intended path, especially during cornering or lane changes. High lateral velocities can lead to oversteer or understeer, where the vehicle either turns more sharply or less sharply than intended. Effective control of lateral velocity is essential for maintaining stability and preventing accidents, particularly in high-speed driving or adverse weather conditions. Advanced vehicle dynamics control systems, such as ESC and TCS, monitor and adjust both longitudinal and lateral velocities to enhance stability and safety. These systems use a network of sensors to gather real-time data on the vehicle's motion and the road conditions. By analyzing this data, they can make precise adjustments to the braking force, throttle, and steering inputs to maintain optimal stability. For instance, if the vehicle begins to oversteer, ESC can reduce engine power and apply braking to individual wheels to help regain control. Similarly, TCS can prevent wheel spin during acceleration by adjusting the throttle

and brake. The integration of longitudinal and lateral velocity data is crucial for the development of autonomous driving technologies. Autonomous vehicles rely on accurate and continuous monitoring of these parameters to navigate safely and efficiently. Advanced algorithms and machine learning techniques are used to process the velocity data and make real-time decisions. For example, when navigating a sharp turn, the autonomous system must balance both longitudinal and lateral velocities to ensure a smooth and safe maneuver. This involves adjusting the speed and steering angle precisely to maintain stability and adhere to the intended path.

In summary, longitudinal and lateral velocities are fundamental to vehicle dynamics, playing critical roles in ensuring stability, maneuverability, and safety. Longitudinal velocity is crucial for acceleration, deceleration, and braking performance, impacting systems such as ABS, ESC, ACC, and collision avoidance. Lateral velocity, on the other hand, influences how well the vehicle maintains its path and responds to steering inputs. Advanced control systems continuously monitor and adjust both velocities to enhance overall vehicle performance and safety. As the automotive industry advances towards greater automation, the precise control and integration of longitudinal and lateral velocity data will be essential for developing safe and reliable autonomous vehicles.

As tires are the only components connecting the vehicle to the ground, motion control or stability control of vehicles ultimately translates into the control of motor torque and braking torque. The TRFC directly limits the maximum tire forces available for the vehicle. Furthermore, many ADAS or high-level autonomous vehicles require dynamic adjustments in longitudinal and lateral control to enhance vehicle safety based on the TRFC. Understanding and accurately assessing the TRFC are crucial for optimizing the performance and safety of these systems. The main function of ABS is to prevent the wheels from locking during heavy braking and to maintain the traction between the tires and the road at an optimal value. The magnitude of this optimal traction is usually determined based on the TRFC. ABS works by modulating the brake pressure to prevent wheel lockup, thereby maintaining steerability and stability during braking. When the TRFC is high, ABS can allow for more aggressive braking without the risk of wheel lockup. Conversely, when the TRFC is low, such as on icy or wet roads, the ABS adjusts to provide gentler braking to maintain control. ESC systems generate a yaw moment based on the desired yaw rate to ensure the lateral stability of the vehicle. The desired yaw rate normally shows a positive correlation with the TRFC. By continuously monitoring the TRFC, ESC systems can adjust the braking force applied to individual wheels to correct understeer or oversteer conditions. For instance, if the vehicle begins to oversteer, the ESC system can apply the brake to the outer front wheel, generating a counteracting force that helps stabilize the vehicle. Accurate TRFC information allows the ESC system to make precise adjustments, enhancing the vehicle's ability to

maintain its intended path, especially in challenging driving conditions. Active collision-avoidance systems use a variety of sensors to obtain information about the surrounding environment of the vehicle to reduce the risk of accidents. These systems work by assessing the relative distance between the vehicle and potential obstacles and initiating preemptive actions when this distance falls below a safety threshold. This safety distance is negatively correlated with the TRFC. In other words, when the TRFC is low, the safety distance must be increased to account for the reduced traction and longer stopping distances. Conversely, when the TRFC is high, the vehicle can safely operate with a shorter safety distance. By integrating TRFC data, collision avoidance systems can more accurately determine when to initiate braking or evasive maneuvers, thereby reducing the likelihood of collisions. Additionally, TRFC plays a crucial role in the operation of ACC systems. ACC systems maintain a set following distance from the vehicle ahead by adjusting the throttle and brake based on the longitudinal velocity of the vehicle. When the TRFC is high, the ACC system can operate more aggressively, allowing for closer following distances and more responsive acceleration and deceleration. However, when the TRFC is low, the ACC system must adjust to maintain a greater following distance and smoother speed changes to ensure safety. The accurate assessment of TRFC is also essential for the performance of high-level autonomous vehicles. Autonomous driving algorithms rely on precise TRFC data to make real-time decisions about acceleration, braking, and steering. For example, when navigating a sharp turn, the autonomous system must balance both longitudinal and lateral forces to maintain stability. Accurate TRFC information allows the system to adjust the speed and steering angle precisely, ensuring a smooth and safe maneuver.

Moreover, ADAS such as TCS also depend on accurate TRFC data. TCS works by preventing wheel spin during acceleration by adjusting the throttle and brake. When the TRFC is high, TCS can allow for more aggressive acceleration without the risk of wheel spin. Conversely, when the TRFC is low, TCS must apply more conservative throttle control to maintain traction. By continuously monitoring and adjusting based on TRFC, TCS enhances the vehicle's ability to accelerate safely in various road conditions.

In summary, the TRFC is a critical parameter for vehicle dynamics and safety systems. It directly influences the performance of ABS, ESC, active collision avoidance, ACC, and TCS, among others. Accurate TRFC information allows these systems to make precise adjustments, enhancing vehicle stability, maneuverability, and safety. As the automotive industry continues to advance towards greater automation and improved safety features, the importance of accurate TRFC assessment will only grow. Ensuring that active safety systems have reliable TRFC data is essential for optimizing their performance and ultimately contributing to safer roads.

Although the yaw rate, sideslip angle, velocity of a vehicle, and TRFC are crucial dynamic parameters that significantly influence its handling and stability, these parameters cannot be directly measured and require estimation methods for determination. Directly measuring the yaw rate of a vehicle is challenging, as it represents the rotational speed around the vertical axis. Conventional vehicle sensors typically do not provide this precise information, necessitating estimation through alternative measured data and models. Direct measurement of the sideslip angle often requires specialized sensors, such as an inertial navigation system. However, in the case of most conventional vehicles, there is no sensor configuration designed for the direct measurement of the sideslip angle. Traditional vehicle sensors primarily focus on parameters like speed, angular velocity, and acceleration, lacking a dedicated sensor for sideslip angle measurement. Consequently, direct measurement of the sideslip angle is often impractical in many situations due to the absence of specific sensors. For longitudinal velocity, while some vehicles are equipped with speed-measuring sensors such as wheel speed sensors or GPS systems, there are situations where the measurements from these sensors may not be accurate or available. For lateral velocity, traditional vehicle sensors are effective for certain dynamic measurements; they do not provide a direct measurement of lateral velocity. Specific sensors designed solely for the direct measurement of lateral velocity are not commonly integrated into standard vehicle sensor setups. The absence of dedicated lateral velocity sensors limits the availability of direct measurement options. Similarly, TRFC cannot be measured by onboard sensors.

The process of vehicle state estimation relies on an intricate interplay between sensor data, mathematical models, and sophisticated algorithms. Sensors such as GPS, LiDAR, radar, and cameras provide raw data about the vehicle's position, speed, and surroundings. This sensor data is then processed using mathematical models that describe the vehicle's dynamics, including its mass, center of gravity, and aerodynamic properties. These models help in predicting how the vehicle will respond to different inputs, such as steering, acceleration, and braking. Sophisticated algorithms, such as Kalman filters, particle filters, and machine learning techniques, are employed to fuse the sensor data and refine the state estimates. Kalman filters, for example, are used to recursively estimate the state of the vehicle by combining predictions from the mathematical models with real-time sensor data. To this end, researchers have successively proposed various estimation approaches to address the challenge. Based on the above discussion, some key importance for vehicle–road interaction systems can be summarized.

### 1.2.1 Enhancing Safety

State estimation is one of the core technologies for ensuring the safe operation of intelligent vehicles. With accurate state estimation, vehicles can perceive their position, speed, and direction in real time, as well as detect other objects in the

environment, such as pedestrians, other vehicles, and obstacles. This perception capability allows intelligent vehicles to react promptly and avoid collisions and other potential hazards. For instance, if an obstacle suddenly appears in front of the vehicle, state estimation can quickly identify and convey the information to the control system, enabling necessary evasive or emergency braking maneuvers.

### **1.2.2 Improving Driving Efficiency**

Through state estimation, intelligent vehicles can optimize their driving paths and behaviors, thus improving overall driving efficiency. By monitoring vehicle states and traffic conditions in real time, intelligent vehicles can choose the optimal path, avoid congestion, and adjust speed and trajectory based on traffic signals and the behavior of other vehicles. This not only reduces travel time but also lowers fuel consumption and emissions, achieving more environmentally friendly travel.

### **1.2.3 Enhancing Autonomous Decision-making Capabilities**

State estimation empowers intelligent vehicles with autonomous decision-making capabilities, allowing them to make independent judgments in complex and variable traffic environments. For example, when faced with changing traffic signals, pedestrian crossings, and emergency vehicle priority, intelligent vehicles need to quickly assess the current state and make corresponding decisions. Through accurate state estimation, vehicles can promptly obtain necessary information, perform risk assessments, and execute decisions to ensure a safe and efficient driving experience.

### **1.2.4 Supporting ADAS**

State estimation is the foundation for realizing ADAS. ADAS features, such as ACC, lane-keeping assist, and automated parking, rely on accurate state estimation to perceive the vehicle and environmental states. These systems provide necessary driving assistance through real-time monitoring and data analysis, reducing driver burden and enhancing driving safety. For instance, ACC systems can accurately measure the distance and speed of the vehicle ahead through state estimation, adjusting their speed to maintain a safe following distance.

### **1.2.5 The Foundation of Future Traffic Systems**

As technology advances, state estimation's role in future traffic systems will become more prominent. The development of intelligent transportation systems (ITS) relies on efficient communication and coordination between vehicles and

between vehicles and infrastructure, and state estimation provides the foundation for achieving this goal. By sharing and integrating various state data, ITS can achieve more efficient traffic management, reduce congestion and accidents, and improve overall traffic flow.

### 1.2.6 Enhancing User Experience

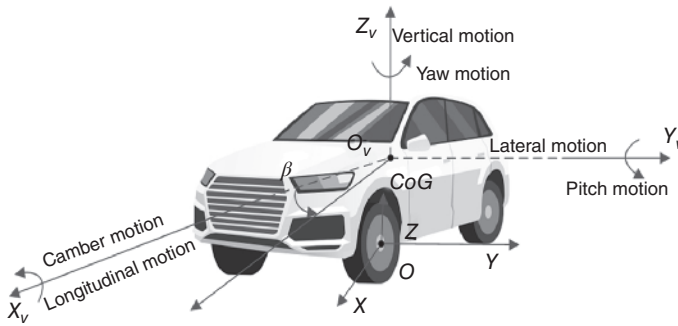
State estimation not only improves the technical performance of intelligent vehicles but also significantly enhances the user experience. Through precise navigation and smooth driving behavior, passengers can enjoy a more comfortable ride. Additionally, various autonomous driving and driver assistance functions supported by state estimation make driving easier and safer, increasing user trust and satisfaction with intelligent vehicles.

In conclusion, the importance of state estimation for intelligent vehicles is undeniable. It is the key technology ensuring safe driving, precise navigation, improved driving efficiency, enhanced autonomous decision-making capabilities, and adaptation to complex environments. As intelligent vehicle technology continues to develop, state estimation will continue to play a central role in advancing autonomous driving and ITS. By continuously improving the accuracy and reliability of state estimation, we can look forward to a future with safer, more efficient, and more comfortable travel methods.

## 1.3 State Estimation Problems of Vehicle–Road Interaction System

According to the definition of vehicle–road interaction system, its key state estimation mainly includes ego-vehicle state estimation, preceding vehicle state estimation, and tire–road friction coefficient identification. Ego-vehicle state estimation usually includes vehicle body dynamic state estimation and model parameter identification. As shown in Fig. 1.2, some typical states include longitudinal and lateral speeds, tire forces, tire cornering stiffness, sideslip angle, the height of the center of gravity, vertical load, etc. Accurate state information is essential for ADAS [13–15]. However, onboard sensors fail to directly obtain this information. Therefore, estimating these vehicle states using only onboard sensors is a hot topic of current research.

Apart from obtaining the ego vehicle state, ADAS usually needs to obtain the state of the preceding vehicle. For example, the ACC system needs to get the preceding vehicle state to achieve better vehicle following. However, the preceding vehicle's state is usually difficult to measure directly via the in-vehicle sensors of the ego vehicle [16]. Therefore, it is a common method to use in-vehicle sensors of



**Figure 1.2** The vehicle coordinate systems.

the host vehicle to obtain some motion information about the preceding vehicle and combine it with a complex vehicle model to estimate the preceding vehicle state. In the vehicle–road interaction system, in addition to obtaining the vehicle state, we also need to get the TRFC. Studies have shown that traffic accidents are more likely to occur on roads with low friction coefficients. The magnitude of the longitudinal and lateral tire forces is related to the TRFC. Hence, the TRFC can indirectly affect vehicle stability [17]. However, the TRFC cannot be measured directly by onboard sensors. Thus, some estimation methods need to be utilized to solve the problem. As can be seen from the above description, the use of estimation methods to obtain the state of a vehicle–road interaction system is an effective solution due to factors such as sensor configuration and cost. The current related studies, despite the fruitful results, still have the following problems:

- 1) In terms of vehicle state estimation, existing studies rarely consider the impact of mass changes on the accuracy of vehicle models. This oversight is significant because the accuracy of estimating critical variables, such as the sideslip angle, is highly dependent on the precision of the vehicle model. Perturbations caused by vehicle mass variation must be accounted for during the estimation process to ensure accurate results. Changes in vehicle mass can occur due to various factors, such as passenger load, cargo, or fuel consumption, and these changes can significantly affect the dynamics of the vehicle. The sideslip angle and tire cornering stiffness are particularly sensitive to mass variations. As the vehicle's mass changes, the distribution of forces on the tires and the overall handling characteristics of the vehicle are altered. This, in turn, impacts the sideslip angle, which is a crucial parameter for maintaining lateral stability. Accurate estimation of the sideslip angle is essential for the effective functioning of stability control systems and other ADAS. Therefore, incorporating the effects of mass variation into the vehicle model is necessary for precise state estimation.

Additionally, the process noise of the vehicle system is often treated as a constant when estimating the vehicle state. However, due to the nonlinearity of the vehicle system and the complexity of the driving environment, the time-varying vehicle dynamics cause the estimated process noise to exhibit dynamic characteristics. The assumption of constant process noise can lead to inaccuracies in state estimation, particularly in scenarios involving rapid changes in driving conditions, such as sharp turns, sudden accelerations, or varying road surfaces. It is crucial to consider the dynamic nature of process noise and its impact on state estimation accuracy.

In practical applications, sensor data loss is a common phenomenon that further complicates vehicle state estimation. Most existing research focuses on the effect of sensor measurement noise on estimation accuracy, rarely considering the impact of sensor data loss. Sensor data loss can occur due to communication issues, hardware malfunctions, or environmental factors. When sensor data is lost, the state estimation algorithms must rely on incomplete information, leading to potential inaccuracies. Effective state estimation must account for the possibility of data loss and implement strategies to mitigate its impact. Furthermore, the noise from sensors is not always Gaussian white noise; it can also be colored noise. In real road driving scenarios, the type of noise from sensors is uncertain and can vary depending on the environment and sensor conditions. Gaussian white noise is a common assumption in many state estimation algorithms because of its simplicity and mathematical convenience. However, this assumption does not always hold true in real-world conditions. Colored noise, which has a correlation structure, can arise from various sources such as road texture, weather conditions, or electromagnetic interference. Ignoring the presence of colored noise can lead to significant errors in state estimation. The multifactorial nature of vehicle state estimation, involving mass variations, dynamic process noise, sensor data loss, and the presence of colored noise, makes it a challenging problem. Addressing these factors requires the development of robust and adaptive state estimation algorithms that can handle the uncertainties and complexities of real-world driving scenarios. For instance, advanced filtering techniques such as adaptive Kalman filters or particle filters can be employed to better account for dynamic process noise and sensor data loss. These filters can adjust their parameters in real time based on the observed data, improving the accuracy of state estimation. In conclusion, accurate vehicle state estimation is critical for the safe and efficient operation of intelligent vehicles. To achieve this, it is necessary to consider the influence of changes in vehicle mass, dynamic process noise, sensor data loss, and the presence of colored noise.

- 2) In terms of the prediction of the motion state of the preceding vehicle, the use of V2V communication for state prediction can effectively avoid the problem

that the in-vehicle sensor is disturbed by the environment and causes the estimation accuracy to decrease. Existing studies estimating the longitudinal and lateral states of the preceding vehicle require a combination of two different models and assume that they are uncorrelated. In addition, estimating the state of the preceding vehicle based on V2V communication is currently a time-triggered prediction method, which lacks an effective mechanism to achieve a balance between communication rate and estimation accuracy. This information transmission mechanism makes the vehicle regularly broadcast its movement information regardless of whether other vehicles need the data, which will inevitably occupy too much bandwidth. In addition, wireless communication usually has the problem of data packet loss. Data loss can occur for a variety of reasons, such as cyberattacks. Once some key sensor data is lost, it will inevitably affect the estimation accuracy of the vehicle state. Furthermore, unknown system dynamics usually have a direct impact on system state estimation and control. Therefore, the model parameters of the vehicle, such as the vehicle mass, can directly affect the accuracy of the model and consequently reduce the estimation performance of the vehicle state. Although many research efforts are devoted to the state estimation of connected vehicles, these studies seldom consider the effect of model parameters perturbation and packet loss simultaneously.

- 3) In terms of predicting the motion state of preceding vehicles, leveraging V2V communication for state prediction can effectively mitigate issues arising from in-vehicle sensor disturbances due to environmental factors, thereby preserving estimation accuracy. Current research focusing on estimating the longitudinal and lateral states of preceding vehicles typically involves combining two different models and assuming their independence. However, estimating the state of preceding vehicles using V2V communication currently relies on a time-triggered prediction method, which lacks an efficient mechanism to balance communication frequency and estimation precision. This transmission mechanism mandates vehicles to regularly broadcast their movement data, irrespective of whether other vehicles require this information, potentially monopolizing bandwidth resources unnecessarily. Furthermore, wireless communication commonly encounters challenges like data packet loss, stemming from causes such as cyberattacks. Loss of critical sensor data inevitably undermines the accuracy of vehicle state estimation. Moreover, unknown system dynamics significantly impact state estimation and control. Vehicle model parameters, such as mass, play a pivotal role in model accuracy and consequently influence vehicle state estimation performance.

Despite extensive research efforts devoted to connected vehicle state estimation, studies seldom address the concurrent effects of model parameter perturbations and packet loss. Addressing these challenges necessitates innovative

approaches in vehicle state estimation methodologies. Enhanced utilization of V2V communication can mitigate reliance on potentially compromised in-vehicle sensors, ensuring more reliable estimation results. However, current methodologies rely on time-triggered transmission, lacking adaptive mechanisms to optimize communication rates based on real-time needs, which can lead to inefficient bandwidth usage. Additionally, managing data packet loss in wireless communication is crucial. Implementing robust error correction and redundancy techniques can help mitigate the impact of packet loss on state estimation accuracy. Furthermore, considering the influence of unknown system dynamics on model parameters is essential. Incorporating adaptive modeling techniques that account for parameter variations, such as vehicle mass, can improve the robustness and accuracy of state estimation algorithms. Despite advancements in connected vehicle technologies, the integrated consideration of model parameter uncertainties and communication challenges remains underexplored in state estimation research.

In the realm of TRFC identification, significant strides have been made in improving estimation techniques. However, the impact of parameter perturbations on estimation accuracy remains largely overlooked. For instance, inaccuracies in vehicle mass parameters can lead to deviations in estimated axle forces, subsequently affecting the precision of TRFC estimation. These deviations arise because variations in vehicle mass alter the distribution of forces on tires, influencing their frictional interaction with the road surface. Many hybrid estimation methods enhance TRFC estimation accuracy through weighted fusion of results from multiple models. Yet, a common limitation is that each model updates its estimates based solely on its previous predictions, without adapting to real-time conditions. This static approach can constrain accuracy in complex driving scenarios where dynamics rapidly change. To address this, dynamic adjustment of model weights based on current driving conditions is essential for achieving optimal TRFC estimation performance.

Moreover, existing TRFC estimation approaches often overlook the impact of missing sensor measurements on accuracy. Data loss from onboard sensors is prevalent, resulting from various factors such as communication disruptions or sensor malfunctions. The incomplete transmission of sensor signals to the estimation system can lead to incomplete or unreliable data inputs, thereby compromising the accuracy of TRFC estimates. Furthermore, traditional model-based methods typically assume precise knowledge of noise statistical characteristics for optimal results. This assumption is often unrealistic in practical scenarios where noise characteristics may vary or be inadequately understood. Data-driven approaches offer promise but face challenges related to data collection, quality, and the ability to generalize across diverse driving conditions. Both model-based and data-driven approaches require real-time access to accurate sensor data

to function effectively. Addressing data loss and developing noise-adaptive algorithms are critical steps toward improving the robustness and applicability of TRFC estimation methods. Adaptive algorithms can dynamically adjust to fluctuations in sensor data quality and availability, thereby enhancing estimation accuracy under real-world conditions. In conclusion, advancing TRFC estimation methods requires addressing the complexities introduced by parameter perturbations, adapting to dynamic driving conditions through flexible model weighting, and mitigating the impact of sensor data loss with noise-adaptive algorithms.

## 1.4 Overview and Organization of the Book

To address the above problems, this book gives the corresponding technical solutions for ego-vehicle state estimation, the preceding vehicle state estimation, and TRFC identification, and carries out simulation and real-vehicle verification. The chapters are organized as follows.

In Chapter 2, the principles of the extended Kalman filter (EKF) are first introduced, and an adaptive fault-tolerant EKF is established for vehicle state estimation in cases of data loss. In Chapter 3, a fuzzy adaptive robust cubature Kalman filter is established to improve the vehicle state estimation accuracy by considering the effects of uncertainties in model parameters and noise parameters. Furthermore, in order to construct a vehicle state estimation method that adapts to multiple noises, a fusion of physical and data-driven estimation methods is introduced. In Chapter 4, a method for estimating the state of the preceding vehicle under event triggering is established by utilizing the V2V communication technology, which can effectively deal with the impact of data loss on the estimation accuracy and can effectively save communication resources at the same time. Furthermore, while considering model parameter uncertainty and data loss effects, a strong tracking event-triggered cubature Kalman filter is designed to enhance estimation accuracy. In Chapter 5, the problem of TRFC under complex operating conditions is investigated, and an interactive multi-model identification method is designed to estimate the TRFC. Furthermore, a fault-tolerant estimation scheme is established to realize the accurate estimation of TRFC considering the sensor data loss problem. Finally, in order to improve the applicability of the estimation method, such as multiple noise adaptation, a model-based learning method is designed to estimate the TRFC. Summaries and recommendations are presented in Chapter 6.

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