Chapter 6
Vehicle Reference Lane Calculation for Autonomous Vehicle Guidance Control

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6.1 Introduction

Autonomous vehicles need smart sensors, actuators, additional road information, and control devices to achieve their tasks for longitudinal and lateral vehicle guidance control [1]. Recently presented prototype vehicles [2, 3] use radar sensors in combination with actuators for engine and brake control for longitudinal vehicle guidance and camera systems in combination with steering actuators for lateral vehicle guidance. Additional sensors like LIDAR and GPS with detailed map data, which nowadays are installed in prototype vehicles, are used more for research purposes [4]. From all possible sensor technologies for lateral vehicle guidance, the most important sensor information for the actual driving situation is provided by the camera system. The online image processing system of the camera module detects the lane markings of the vehicle lane. The camera software determines the distance of the actual vehicle position on the track to the left and right lane marking, as well as the heading angle of the vehicle to the lane markings on the street. This information is provided in real time via the vehicle bus system to the electronic control unit (ECU) which performs the lane-keeping control task. Besides the information of the actual position of the vehicle on the track or its predicted path, which can be designed according to [5, 6], the lane guidance controller needs also additional information about the desired reference position value of the vehicle. This reference lane is the desired track lane where the vehicle should ideally drive

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on the track. This value is propagated to the lane-keeping controller by the use of a
desired lane offset signal. This desired lane offset signal, or reference lane signal, is
usually defined to be zero in the middle of the lane and positive with right-hand side
offset values. The controller calculates its controller deviation from this reference
value and the current position of the vehicle on the track, trying to minimize the
controller deviation by driving the actuators of the system accordingly [7]. It is
obvious that the performance of the overall lane-keeping controller is, among others,
mainly influenced by the quality of this reference lane input. The reference lane
calculation module therefore belongs to the most important controller parts for the
lateral vehicle guidance task in autonomous vehicles [8, 9].

One simple approach for reference lane calculation is to keep the vehicle in the
middle of the accessible lane, which means to provide the lane-keeping controller
with an offset signal of zero. This “mid-lane” approach is widely used by passenger
car lane-keeping systems, e.g., seen in [10] and [11]. The “mid-lane” approach
shows good results when used in passenger cars without any trailer attached. For
vehicles with more complex driving dynamics like vehicles with trailer attached or
heavy truck vehicles like truck–semitrailer combinations, the “mid-lane” approach
is not sufficient anymore. This is not only because of the bigger dimension of these
vehicles but also because of different driving dynamics and especially because of
additional risk potential arising, for example, from the tractrix. Drivers of heavy
trucks with trailer attached or drivers of truck–semitrailer vehicles therefore often
have to choose different vehicle tracks than driver of passenger cars. The task of
this paper is to design a reference lane calculation system which meets also the
complex requirements of heavy truck and truck–semitrailer driving. Due to the fact
that this task is the more general case of reference lane calculation, the easier task
for calculating the reference lane for smaller vehicles with simpler driving dynamics
like passenger cars will be included in the proposed reference lane calculation
method.

### 6.2 Vehicle Lane-Keeping Boundaries and Requirements

The first step for designing a reference lane calculation system is to gain some
overview of the fundamental boundaries of road tracks and the possible diversity
of vehicle parameters which have influence on reference lane selection. The
environmental boundaries for autonomous vehicles were defined by the geometry
of the roads and the associated speed limitation regulations. A short overview of the
requirements regarding the road geometry and speed limitation is given in Table 6.1,
which shows typical road curvature and road width with the associated design speed
regulations.

The columns A, B, and C list different road categories which refer to German
guidelines for road construction [12, 13]. All categories are used for national and
rural roads; categories B and C are permitted for use within built-up areas. For class
C roads, it is furthermore allowed to have adjoining building next to the road. The
Table 6.1 Road characteristics with minimum road radius information [12, 13]

| Road category | A       | B       | C       |
|---------------|---------|---------|---------|
| Lane width (m)| 2.75–3.75| 2.75–3.75| 2.75–3.75|
| Design speed (km/h) | Minimum road radius for category and speed (m) |
| 40            | –       | –       | 40      |
| 50            | –       | 80      | 70      |
| 60            | 135     | 125     | 120     |
| 70            | 200     | 190     | 175     |
| 80            | 280     | 260     | –       |
| 90            | 380     | –       | –       |
| 100           | 500     | –       | –       |
| 120           | 800     | –       | –       |

Lane width of a road is chosen in dependence of traffic volume and other factors, but generally it can be supposed that the selected road width decreases from category A to C. Roads with narrow lanes are challenging for lateral vehicle guidance systems because of less safety buffer for keeping the vehicle on track. For vehicles with trailer attached, the additional risk of tractrix hazards increases with reduced lane width and reduced curvature radius. For reference lane calculation development, the environmental boundaries should therefore be selected to cover these use cases best possible. One possible example of an environmental design setup will be a narrow road with small curvature radius, which will typically be used at relatively low vehicle speeds. According to this example, the road type C with small lane width and 50 m curvature radius, used at design speeds of 40 km/h, could be selected. Typical driving scenarios would be, for example, at exits of highways or curvy country roads. The vehicle parameter which influences the reference lane selection the most is the wheelbase of the vehicle as well as the type of the attached trailer or semitrailer. These parameters have influence on the track offset when cornering, which the driver has to take into account when choosing the vehicles lane for avoiding collisions in the tractrix area. The track offset is the difference of turning radius between the first and the last axle of a vehicle when cornering. When surveying vehicles with trailers attached, three main vehicle categories can be separated. These categories are the truck–semitrailer vehicle, the vehicle with rigid drawbar trailer, and the vehicle with pivot plate trailer. Figure 6.1 shows these different vehicle types in cornering maneuvers with the most important vehicle parameters for track offset determination.

As can be found, under Ackermann conditions the track offset calculation equations, as shown in Eq. (6.1), do not differ between truck–semitrailer and truck with rigid drawbar trailer [14]:

$$\Delta = r - \sqrt{r^2 - l_{Tk}^2 + l_{Co}^2 - l_{Ti}^2}$$
When adapting appropriate vehicle parameters, the track offset calculation relationship is also suitable similarly for passenger cars with trailer, truck with rigid drawbar trailer, and truck–semitrailer applications. The truck with pivot plate trailer has an additional pivot point which leads to a slightly different track offset equation, as shown in Eq. (6.2):

$$
\Delta = r - \sqrt{r^2 - l_{tk}^2 + l_{co}^2 - l_{db}^2 - l_{tl}^2}
$$

Both equations require Ackermann conditions, thus applicable in cornering maneuver at low vehicle speed. Considering this driving situation for reference lane calculation, the track offset differences between these three vehicle types have to be examined closer. The results of the gained lane offset $\Delta$, based on typical vehicle parameters of vehicles of each category, are shown in Table 6.2. The comparison of these different vehicle types and their associated vehicle dynamics states under Ackermann conditions on a road of category C at low vehicle speed shows that the truck–semitrailer vehicle typically has the biggest lane offset, whereas the truck with pivot plate trailer has the smallest.

Summarizing the examinations of environmental boundaries and possible vehicle types for most general reference lane calculation design, it can be found that additional risk of tractrix hazards will occur mainly on narrow and curvy roads which are designed for comparatively low vehicle speeds related to the German guidelines for road construction. As can be seen in Table 6.2, the biggest lane offset in these driving situations will be gained by the truck–semitrailer vehicle type ($\Delta = 0.72$ m). For the purpose of designing a reference lane calculation method, which is able to consider the abovementioned boundaries for the most general case, the truck–semitrailer vehicle type has to be chosen.
### Table 6.2 Parameters, for example, calculation with Ackermann conditions

| Length parameter (m)                     | Truck with pivot plate trailer | Truck with drawbar trailer | Truck with semitrailer |
|-----------------------------------------|--------------------------------|----------------------------|------------------------|
| Curve radius \( r \)                   | 50                             | 50                         | 50                     |
| Truck wheelbase \( l_{Tk} \)            | 5.5                            | 4.9                        | 3.7                    |
| Coupling point (fifth wheel) to rear axle \( l_{Co} \) | 2.4                            | 1.8                        | 0.65                   |
| Drawbar \( l_{Db} \)                    | 3                              | –                          | –                      |
| Kingpin to trailer axle or trailer wheelbase \( l_{Tl} \) | 5.17                           | 6.43                       | 7.63                   |
| Lane offset \( \Delta \)               | 0.61                           | 0.62                       | 0.72                   |

### 6.3 Vehicle Driving Situation Analysis

A reference lane calculation method which is not adapted to the driver’s demands will autonomously take steering actions which must or will be actively corrected by the driver. Such a system behavior will be annoying to the driver, which will lead in the end to a deactivation of the assistance system by the driver, if that is possible, or at least will lead to a dishonored system with accordingly bad customer response. For designing a reference lane calculation system, it is therefore essential to analyze the driving behavior of a truck–semitrailer vehicle and the driving style of the users of such vehicles in different driving situations. The first driving situation which has to be analyzed is the simple straightforward driving situation. When a driver of a passenger car will mainly choose the mid of the lane as reference, to get an equal safety buffer to the left and right lane markings, the driver of a truck–semitrailer will choose a reference lane with an offset to the right. This is reasonable because of the bigger dimensions of a truck. Especially the bigger mirrors are in danger to get involved in collisions with the mirror of a truck coming along the opposite lane. Figure 6.2 shows this situation for three different track widths. As track width is declining, also the offset must be chosen smaller. If track width is getting too small to have enough buffer space for choosing a reference lane, the offset is getting zero which leads in the end to mid-lane driving, shown with the truck on the right-hand side of the figure.

When driving vehicles with long wheelbase or vehicles with trailer or semitrailer attached, the driver has to keep attention of the tractrix and track offset of the rear wheels of the vehicle at every cornering situation. Figure 6.3 shows an example of a dangerous situation regarding this issue. The red truck is guided by a “mid-lane” reference lane on a road with 3.75 m width, which is a quite common lane width for highway and larger countryside roads. Nevertheless the rear wheels of the red semitrailer are already leaving the lane and potentially compromising the traffic on the opposite lane.

The green truck–semitrailer uses an adapted (green) reference lane, with an offset to the outside of the turn, taking the track offset of the vehicle in account. This truck–
Fig. 6.2  Driving situation: Straightforward driving with lane width change, mid-lane guidance (chain dotted line), and adapted lane guidance (solid line)

Fig. 6.3  Driving situation: Left-turn driving with mid-lane guidance (chain dotted line) and adapted lane guidance (solid line)

Fig. 6.4  Driving situation: Right-turn driving with mid-lane guidance (chain dotted line) and adapted lane guidance (solid line)

The semitrailer is able to perform the left-hand side cornering safely without leaving the traffic lane. Especially when performing a right-hand side cornering maneuver, the driver of a truck–semitrailer vehicle has often to follow a comparatively sophisticated reference lane, as Fig. 6.4 shows. First the driver of the truck–semitrailer comes from a straight-ahead driving situation, which leads him to drive
the vehicle with an offset to the right lane limitation, as mentioned above. To accomplish the cornering without running the risk of departing the traffic lane with the rear wheels of the semitrailer unintentionally, the driver has to adapt his right-hand side reference lane offset to a left-hand lane offset (solid reference lane). If the driver uses the mid-lane reference approach instead (red chain dotted line), the rear wheels of the semitrailer will leave the traffic lane. If the side verge is not able to carry the wheel load of the semitrailer properly, such a situation could easily lead to a rollover accident.

These presented main driving maneuvers cover most of the standard driving situations a driver or an autonomous vehicle has to deal with. Nevertheless there are many more additional driving situations which might occur during a drive. Such additional driving situations, for example, could be obstacles like a stopped vehicle at the side verge. In this situation the driver will take the maximum possible driving offset to the left to have as much safety buffer to this obstacle when passing it. Traffic jams give a further situation where special driving maneuvers like forming an emergency corridor have to be performed. Even if emergency vehicles with flashing blue lights are going to pass, the driver has to react with an adapted reference lane, which will be a maximum offset to the right-hand side in this case.

6.4 Model-Based Reference Lane Calculation Method

Taking the requirements from Sects. 6.2 and 6.3 in consideration, a reference lane calculation algorithm for lane keeping has to comply with the following main tasks:

- **Vehicle Safety Task**: The system has to keep the vehicle in track which also includes preventing the wheels of the vehicle trailer from leaving the road. This means that the tractrix of the vehicle has to be monitored permanently. Therefore the possible reference lane selection within the traffic lane is limited not only by track width but also by tractrix limitations.

- **Driving Comfort Task**: The system has to be adapted to the driver’s needs and driving habits at least in the most common driving situations to gain high driver acceptance and high-quality customer response.

- **Connected Emergency Task**: An advanced reference lane calculation system also has to include information from ambient connected vehicles or infrastructure devices in the reference lane calculation process.

To meet the safety requirements, in most general case, the truck–semitrailer vehicle is chosen for designing the reference lane calculation algorithm, because the biggest track offset is gained by this vehicle type as shown in Sect. 6.2. When driving in straightforward driving situations, the possible lane selection isn’t affected by the tractrix, so the limitations are in fact the left and right lane markings of the traffic lane the vehicle is actually driving on. When performing a cornering situation, however, the tractrix will take effect and the traffic lane limitations will be lowered due to tractrix limitations. To calculate the tractrix limitations, online in
the driving vehicle, a model-based approach based on a single-track model of the truck–semitrailer vehicle, as shown in Fig. 6.5, could be used.

As could be seen in the figure, the vehicle is performing a left-hand side cornering maneuver with kink angle $\gamma$ and track offset $\Delta$. To assure safe cornering the radius of the vehicle $r_{Tk,f}$ must be adapted by the track offset $\Delta$ so that the turning radius of the trailer $r_{Tl,min}$ stays within the traffic lane borders. Because online measurement of the track offset is not possible, the offset has to be calculated from available vehicle measurement signals. To determine the track offset of the vehicle, generally the kink angle has to be known. Due to the fact that the vehicle kink angle is not measured by sensors too, a real-time capable kink angle observer has to be designed, which is able to determine the necessary kink angle to pass the road curvatures ahead of the vehicle [15]. The information of the road ahead, which is a necessary input for the kink angle observer, could be gathered by a camera system, which indeed provides the reference lane calculation system with the required information of curvature, vehicle position within the lane and heading angle of the vehicle. By the use of this information, it is possible to set up a track offset calculation module which calculates the necessary track offsets of the road curvature with a beneficial look-ahead functionality. As human drivers do, every lateral vehicle controller needs controller reference values with some look-ahead capacity, to gain the best possible performance at vehicle guidance task. When designing the reference lane calculation module for lane-keeping controllers, this can be assured as mentioned above, by a proper use of the camera look-ahead information available.

For designing the kink angle observer, the single-track model of a truck–semitrailer, as shown in Fig. 6.6, is used. The kink angle $\gamma$ could generally be determined by numerical integration of kink angle rate $\dot{\gamma}$:

$$\gamma_t = \dot{\gamma} \cdot t_1 + \gamma_{t_1-t_1}$$  \hspace{1cm} (6.3)

The kink angle rate $\dot{\gamma}$ is the difference of the yaw rate of the truck $\dot{\psi}_{Tk}$ and yaw rate of the semitrailer $\dot{\psi}_{Tl}$:

$$\dot{\gamma} = \dot{\psi}_{Tk} - \dot{\psi}_{Tl}$$  \hspace{1cm} (6.4)
The yaw rate of the truck $\dot{\psi}_{Tk}$ could be represented by use of the equations of the single-track model as Eq. (6.5) shows. The yaw rate is calculated from vehicle steering angle $\delta$, the front wheel speed $v_{Fa}$, and the sideslip angle $\alpha_{Fa}$ of the front wheels. Unfortunately the sideslip angle could not be measured online in vehicle when not using expensive measurement equipment; therefore Eq. (6.5) could not directly be used for determining the yaw rate. Alternatively the directly measured yaw rate of the truck by the vehicle’s yaw rate sensor, used for the electronic stability program (ESP), could be used:

$$
\dot{\psi}_{Tk} = \frac{v_{Fa}}{l_{Tk}} \cdot \sin \delta \cdot \cos \delta - \frac{v_{Fa} \cdot \cos \delta}{l_{Co}} \cdot \sin \alpha_{Fa}
$$

(6.5)

The yaw rate of the semitrailer could accordingly be represented by using a single-track model as Eq. (6.6) shows. The yaw rate is determined besides geometrical vehicle parameters, from steering wheel angle $\delta$, front wheel speed $v_{Fa}$, and kink angle $\gamma$:

$$
\dot{\psi}_{Tl} = \frac{v_{Fa} \cdot \cos \delta \cdot \sin \delta}{l_{Tk}} \cdot \frac{l_{Tk,b}}{l_{Co}} \cdot \cos \gamma
$$

(6.6)

With Eqs. (6.4), (6.5), and (6.6), we get the calculation method for the kink angle rate:

$$
\dot{\gamma} = \frac{v_{Fa}}{l_{Tk}} \cdot \sin \delta \cdot \cos \delta - \frac{v_{Fa} \cdot \cos \delta}{l_{Co}} \cdot \sin \alpha_{Fa} - \frac{v_{Fa} \cdot \cos \delta \cdot \sin \delta}{l_{Tk}} \cdot \frac{l_{Tk,b}}{l_{Co}} \cdot \cos \gamma
$$

(6.7)

The kink angle could be calculated from Eq. (6.3) by the use of sensor input information of vehicle speed, yaw rate of the truck, and necessary steering angle which is gained from the camera curvature information, performing a numerical integration. With the knowledge of kink angle, the track offset has to be determined. When assuming cornering maneuvers under Ackermann conditions, this can be
achieved with simple trigonometric equations. The assumed simplifications of the Ackermann conditions are:

- Low vehicle speed with almost no longitudinal tire forces (no slip).
- No influence of lateral acceleration, no sideslip angle, and therefore no lateral tire forces.
- The prolongation of the tire axles meets in one circular center point.

Compared to vehicles without trailer, truck–semitrailer vehicles or vehicles with trailer attached tend to drive cornering maneuvers at relatively low lateral accelerations to avoid rollover risks. Typically values for lateral accelerations during lane change maneuvers, for example, are in a range from 0.2 to 0.5 m/s² [16]. So the Ackermann assumptions generally comply quite well with the use cases of the proposed application. Furthermore typically tractrix calculations are essential especially at relatively steep cornering maneuvers which anyway were performed at lower speeds, for example, at highway exits or curvy country roads, as shown in Sect. 6.2. So the Ackermann assumptions are suitable for use in track offset determination task for reference lane calculation.

The trigonometric relationship of the single-track vehicle model under Ackermann assumptions is shown in Fig. 6.7 for a truck–semitrailer vehicle. The steering angle $\delta$ can be calculated with Eq. (6.8) from wheelbase of the truck $l_{Tk}$ and the

![Fig. 6.7 Single-track model of a truck–semitrailer combination](image-url)
turning radius of the front wheels \( r_{Tk,f} \) \cite{17, 18}:

\[
\sin(\delta) = \frac{l_{Tk}}{r_{Tk,f}} \quad (6.8)
\]

The necessary turning radius of the front wheels \( r_{Tk,f} \) depends on the road curvature \( c_r \) which the vehicle is driving at. For autonomous vehicles with camera-based lateral vehicle guidance, the curvature information of the road ahead is provided by the lane detection camera. In case of GPS-based lateral vehicle guidance, the curvature information is available from road map data:

\[
r_{Tk,f} = \frac{1}{c_r} \quad (6.9)
\]

By the use of Eqs. (6.8) and (6.9), a necessary steering angle \( \delta \) for driving a road curvature \( c_r \) can be calculated with Eq. (6.10). This steering angle, depending on the road curvature ahead, can be used as input for the kink angle observer to calculate the kink angle arising when driving the curvature:

\[
\delta = \arcsin \left( \frac{l_{Tk}}{r_{Tk,f}} \right) = \arcsin \left( l_{Tk} \cdot c_r \right) \quad (6.10)
\]

First step for track offset calculation is the determination of the minimum turning radius \( r_{Tk,min} \) at the rear wheels of the truck. The required cornering radius of the front wheels \( r_{Tk,f} \) could be gained from the camera curvature information. The minimum cornering radius of the rear wheels \( r_{Tk,min} \) could then be calculated with Eq. (6.11) by use of the wheelbase \( l_{Tk} \):

\[
r_{Tk,min} = \sqrt{r_{Tk,f}^2 - l_{Tk}^2} \quad (6.11)
\]

Next step is the calculation of the turning radius at the semitrailer coupling \( r_{Co} \) from minimum rear wheel cornering radius \( r_{Tk,min} \) with Eq. (6.12):

\[
r_{Co} = \sqrt{r_{Tk,min}^2 + l_{Co}^2} \quad (6.12)
\]

The angle \( \varepsilon \) which is the angle between turning radius of the semitrailer coupling and the vehicles longitudinal axis could be determined by Eq. (6.13):

\[
\varepsilon = \arccos \left( \frac{l_{Co}}{r_{Co}} \right) \quad (6.13)
\]

By use of \( \varepsilon \) and the kink angle \( \gamma \) from the kink angle observer module, the minimum turning radius of the trailer \( r_{Tl,min} \) is given in Eq. (6.14):

\[
r_{Tl,min} = r_{Co} \cdot \sin (\varepsilon - \gamma) \quad (6.14)
\]
Finally the track offset $\Delta_{\text{tractrix}}$ could be calculated as difference between cornering radius of front wheels $r_{Tk,f}$ and minimum cornering radius of trailer axle $r_{Tl,\text{min}}$:

$$\Delta_{\text{tractrix}} = r_{Tk,f} - r_{Tl,\text{min}}$$ (6.15)

The track offset $\Delta_{\text{tractrix}}$ gives the possibility for real-time calculation of required lane space for driving an oncoming traffic lane curvature safely regarding tractrix hazards. Therefore this information is used to generate online safety limitations for possible reference lanes for left-hand side and right-hand side cornering maneuvers. Within this limitation the reference lane could be set freely from safety sight of view. It is recommended to use this potential to add solutions for additional requirements, for example, to gain higher driving comfort. Therefore requirements from driver habits could be taken in consideration to gain the best possible driving comfort. As seen in Sect. 6.3, the driver of the considered truck–semitrailer vehicle will tend to drive this type of vehicles with an offset to the right-hand side. To meet this requirement in the proposed reference lane calculation method, a nonlinear approach of traffic lane width dependent on comfort offset calculation, as shown in Eq. (6.16), is used:

$$\Delta_{\text{comfort}} = \frac{\Delta_{\text{lane,set}}}{w_{l,\text{set}} - w_{\text{veh}}} \cdot \max [(w_{l} - w_{\text{veh}}), 0]$$ (6.16)

The comfort track offset $\Delta_{\text{comfort}}$ depends from vehicle width $w_{\text{veh}}$ and track width $w_{l}$. The parameterization of the nonlinear offset function is done by setting a reference offset point $\Delta_{\text{lane,set}}$ at a certain track width $w_{l,\text{set}}$, which can be freely chosen accordingly to the needs of the users. If vehicle width $w_{\text{veh}}$ is getting bigger than actual track width $w_{l}$, the comfort offset is set to zero to perform a mid-lane vehicle guidance approach at this driving scenario. The user of the vehicle could also be enabled to set different comfort parameters, e.g., the reference offset point, of the reference lane calculation software module for adapting vehicle reference lane calculation to his/her needs. Autonomous vehicles also include additional functionalities for special driving situations which have also to be taken in consideration for reference value generation software algorithms. These driving situations include emergency situations like forming emergency corridors when traffic jams occurs or setting the driving lane offset to the maximum possible right direction for enabling emergency vehicles to pass. Another driving situation with high accidental risk is the situation when the vehicle has to pass a stopped vehicle or any other obstacle at the side verge. Again the appropriate reaction would be to set the reference lane offset to the left limit to gain maximum buffer space to the obstacle on the right. To perform these situations, a special emergency track offset is calculated as Eq. (6.17) shows:

$$\Delta_{\text{emergency}} = \frac{\max [(w_{l} - w_{\text{veh}}), 0]}{2} \cdot \text{sign}(E_{\text{left, right}})$$ (6.17)
The emergency offset is determined so that the vehicle is guided to the border of the actual lane width of the appropriate side to generate a safety buffer. For activation of the emergency reference lane calculation, additional input and further software modules are used. This module includes also information from other surrounding vehicles and infrastructure devices. The gained information is preprocessed by additional software modules, and the reference lane generation module finally gets the information $E_{\text{left, right}}$ if an emergency lane is needed. The choice of the lane side which is appropriate for the actual emergency situation is defined by the sign of $E_{\text{left, right}}$ in Eq. (6.17). To generate the lane reference output value, the calculated track offsets for vehicle safety, driving comfort, and connected emergency have to be merged together to one target value for the lane-keeping controller of the autonomous vehicle. This task is performed by use of a prioritization logic. The highest priority is to keep the vehicle safely on track. In standard driving situations, Eq. (6.18) is therefore used to limit the determined comfort driving lane with the tractrix limitations. The minimum function $\min_0$ of Eq. (6.18) is used to set the minimum around zero to be able to use left- and right-hand side offsets around the center lane of the track:

$$\Delta_{\text{reference}} = \min_0 [\Delta_{\text{tractrix}}, \Delta_{\text{comfort}}] \quad (6.18)$$

In cases of emergency situations, the comfort lane is substituted by the appropriate emergency lane, which leads the driving comfort lane having the lowest priority. When using the emergency lane, keeping the vehicle on track has again a higher priority than performing the emergency lane. Equation (6.18) can therefore be used by replacing the driving comfort lane with the emergency lane, shown in Eq. (6.19):

$$\Delta_{\text{reference}} = \min_0 [\Delta_{\text{tractrix}}, \Delta_{\text{emergency}}] \quad (6.19)$$

By using this approach, the prioritization levels of the calculated track offsets are given by the vehicle safety with highest priority, emergency lane with mid priority, and the driving comfort with lowest priority.

### 6.5 Functional System Architecture Overview

By use of the developed model-based kink angle observer, it is possible to design a reference lane calculation system which is able to fulfill all the requirements of complex driving dynamics regarding autonomous tractrix observation for truck–semitrailer vehicles. Due to the fact of requirement selection choosing the most general use case in Sect. 6.2, the proposed reference lane calculation method is also valid for vehicle types like passenger car with trailer attached or truck–trailer combinations which generally have less track offset then the truck–semitrailer has. The reference lane calculation method in these cases would only set reference lanes with more safety buffer than a truck–semitrailer would have. Figure 6.8 shows the
functional software architecture of the proposed reference lane calculation system with three main parts: the kink angle observer with track offset calculation, the user-specific reference lane generation, and the output of the desired lane after the tractrix limitation of the generated user reference lane. The input stage gathers sensor information from the vehicle bus system, like vehicle speed and steering angle, as well as from the camera system with signals like distance to left/right lane marking and curvature of the lane. This information is used by the subsequent operation modules to calculate the reference lane $y_{ref}$ and the left/right lane limitations ($L_l$ and $L_r$). The reference lane gives the desired position of the vehicle on the track which is performed and adjusted via the lateral lane controller of the autonomous system. The limitation values $L_l$ and $L_r$ accomplish the driver task of observing the tractrix and ensuring that the rear wheels of the trailer or semitrailer stay on the road in all driving situations. To calculate the tractrix limitations, the kink angle observer, as shown in Sect. 6.4, and the actual lane curvature information from camera system are used to determine the track offset. This track offset is then propagated to the reference lane correction module, to limit the desired lane to possible values regarding tractrix hazards.

Till reference lane correction module limits the desired lane to safe values, a user-specific reference lane can easily be applied at the vehicle without danger of harming any safety restrictions. The user-specific reference generation module implements the algorithm for vehicle-specific reference lanes which could be in the simplest case a “mid-lane” approach for passenger cars with trailer attached.
these cases the tractrix limitation because of trailer usage is permanently assured by the reference lane correction module. For truck–semitrailer combinations, a simple constant lane offset to the right-hand side could be set to meet the requirements of truck drivers straightforward driving desires. For more advanced solutions, the constant offset could be improved by using an offset value which is dependent from actual traffic lane width. If the lane width is equal to vehicle width, the offset will go to zero and the reference lane will then be the same as in the mid-lane approach. In the user-specific reference generation module, also the emergency lane functionalities are implemented. External information received from infrastructure devices or other vehicles are used to set appropriate reference lanes for the vehicle in different emergency situations. Since there where camera input signals used for calculation modules like in the track offset calculation module, a simple look-ahead functionality of the module output can be ensured. This leads to better performance of the subsequent lane controller in the autonomous vehicle guidance system.

6.6 Example Driving Situations and Module Performance

For performance testing and validation of the reference lane calculation method, different driving situations have to be considered to cover all design requirements. As an example the main driving situations, straightforward driving, left-hand side cornering, and right-hand side cornering, as shown in Sect. 6.3, will be subsequently examined with the implemented software module with a measured driving run. The output of the reference lane calculation procedure is given at Fig. 6.9, where the reference lane offset is shown over simulation time. Preprocessed measurement data were used as input for the simulation run; thus the truck–semitrailer is driving with cruise control 50 km/h on a curvy country road during the simulation. To get a short overview of the driving run on which the simulation analysis is based on, the performed driving situations are listed in Table 6.3 in dependence of simulation time.

A reference lane offset of value zero corresponds to the “mid-lane” approach as indicated by the dashed line in Fig. 6.9. The left and right limitation graphs limit the possible reference lane selection area which is safe regarding possible tractrix hazards. The dark red solid line finally shows the calculated reference lane from the proposed reference lane calculation method. In the first section from simulation time from 0 s to approximately 20 s, the vehicle is in a straightforward driving situation, indicated by the given possible reference lane limits of 40 cm which are equally for the left- and the right-hand side. The reference lane of the vehicle, which is given by the green graph, is chosen with a traffic lane dependent offset. As the figure shows, the offset in this road width situation is approximately 25 cm to the right. From 20 to 40 s, the left limitation is lowered which indicates that the vehicle is performing a slight left-hand side cornering maneuver. Due to the fact that the left limitation doesn’t affect the actual reference lane, the vehicle is able to continue driving with its previously used right-hand side offset. Shortly after simulation time of 40 s, a
steep right-hand side cornering has to be performed. The right limitation calculation uses the information from the camera system and the kink angle observer to detect the oncoming lane curvature. With observer knowledge it is possible to calculate the necessary kink angle to pass this curvature and determine the oncoming track offset in real time.

This information is used to examine the right limitation shown in Fig. 6.9. As can be seen, the right limitation affects the actual vehicle reference lane in that way, that the offset to the right-hand side is lowered to zero in the first stage. When proceeding

Table 6.3 Simulation steps of driving scenario

| Simulation time (s) | Driving situation                       |
|---------------------|----------------------------------------|
| 0–20                | Straightforward driving (ref. Fig. 6.2) |
| 20–40               | Left-hand cornering (ref. Fig. 6.3)     |
| 40–77               | Right-hand cornering (ref. Fig. 6.4)    |
| 77–98               | Straightforward driving (ref. Fig. 6.2) |
| 98–130              | Left-hand cornering (ref. Fig. 6.3)     |
| 130–165             | Right-hand cornering (ref. Fig. 6.4)    |
the cornering maneuver, it is even necessary to set the offset to the left-hand side, to pass safely this steep right-hand side road curvature without having any tractrix hazards. As soon as the road curvature is passed, the reference lane is set back to the lane width dependent offset for straightforward driving situations. Another left-hand cornering maneuver and in comparison to the first a less steep right-hand side cornering situation are following with ongoing simulation time.

### 6.7 Conclusion

This paper presents the recent developments of reference lane calculation methods necessary for advanced driver assistance systems and autonomous driving vehicles. It could be shown that a simple mid-lane approach as used for reference lane determination for passenger cars is not suitable for vehicles with more complex driving dynamics, e.g., vehicles with trailers or semitrailers attached. For designing an advanced reference lane calculation method, it is essential to determine the requirements and boundaries of road environment as well as the possible variety of vehicles where the system is intended to be applied. The truck–semitrailer vehicle type was chosen for developing the reference lane calculation algorithm, because this vehicle type provides the most general case for this task. This selection approach permits the usage of the proposed reference lane calculation method to be used in principal and also for all other vehicle types. A very important design requirement is also to include considerations of vehicle driver desires in different driving situations in the design specification process to gain a system with good customer response and high driver acceptance. This is equally important for percentage of usage of driver-selectable assistance systems as well as for persistent activated autonomous guidance systems. One of the most important safety hazards when driving vehicles with trailers or semitrailers attached is the risks of tractrix accidents. The proposed reference calculation method includes this safety function of permanent tractrix observation as well as a user-dependent reference lane generation and calculation of special reference lanes for emergency situations to provide a system with all necessary safety features in combination with highest possible driving comfort.

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