Driving Behaviours Constraints

I. METHODOLOGY

A. Vehicle Following(VF)

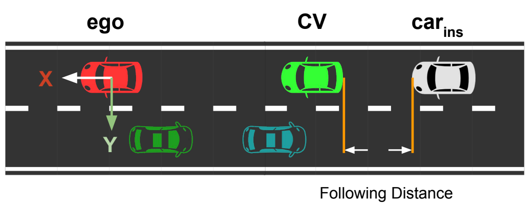

Fig. 1: vehicle following

1) Constraints Applied to V2X Technology: To effectively evaluate V2X technology in generated scenarios, the followed vehicle must belong to the set of vehicles participating in cooperative perception, as constrained by Constraints (1), where V represents the set of vehicles engaged in cooperative perception.

$$car_{bf} \in V \tag{1}$$

2) Initial Position Constraint: The vehicle executing the following behavior is denoted as car_{ins}, while the vehicle being followed is denoted as car_{bf}. A local coordinate system is established with the center of car_{bf} as the origin (see Figure 1). The position of car_{ins} in the i-th frame is labeled as P_i^L. In every frame, the position of car_{bf} remains fixed at the origin. For the initial coordinate generation:Constraint (2) ensures car_{ins} is positioned directly behind car_{bf} with lateral alignment. Constraint (3) restricts the current following distance between car_{ins} and car_{bf} to lie within predefined maximum and minimum thresholds.

$$P_1^L.x < car_{bf}.x \wedge P_1^L.y = car_{bf}.y \tag{2}$$

$$\begin{aligned} MinDistance <= |P_1^L.x - car_{bf}.x| \\ <= MaxDistance \end{aligned} \tag{3}$$

$$MinDistance = car_{bf}.l/2 + car_{ins}.l/2 + MinFD \tag{4}$$

$$MaxDistance = car_{bf}.l/2 + car_{ins}.l/2 + MaxFD \tag{5}$$

Here, MinDistance and MaxDistance denote the minimum and maximum constraints for the distance between the centers of the two vehicles, calculated using Equations (4) and (5), respectively. car.l: Represents the vehicle length. MinFD: Minimum following distance. MaxFD: Maximum following distance.

3) The Motion of Vehicles: During subsequent coordinate generation: P_{i+1}^L and P_i^L represent the coordinates generated for the (i+1)-th and i-th frames, respectively.The relative position of car_{ins} dynamically adjusts based on velocity:If car_{ins}.v $<car_{bf}$.v , then P_{i+1}^L.x=P_i^L.x+dx (where dx $>$0). If car_{ins}.v $>car_{bf}$.v, then P_{i+1}^L.x=P_i^L.x-dx If velocities are equal, the next-frame coordinates remain unchanged. The calculated coordinates must satisfy Constraint (6) and Constraint (7); otherwise, the operation is canceled. Velocity calculations require transforming coordinates from the local coordinate system (centered on car_{bf}) to the world coordinate system. P_i^W=$Martix_{LtoW} \cdot P_i^L$. P_i^W represents the coordinate values in the world coordinate system. $Martix_{LtoW}$ denotes the transformation matrix for converting coordinates from the local coordinate system to the world coordinate system. v_{i+1}=Dis(P_{i+1}^W,P_i^W)/Δ t. The velocity at the (i+1)-th frame is denoted as v_{i+1}, where Δt represents the time interval between consecutive frames. Dis() denotes the function that calculates the Euclidean distance between two points.

$$P_{i+1}^L.x < car_{bf}.x \wedge P_{i+1}^L.y = car_{bf}.y \tag{6}$$

$$\begin{aligned} MinDistance <= |P_{i+1}^L.x - car_{bf}.x| \\ <= MaxDistance \end{aligned} \tag{7}$$

B. Overtaking(OT)

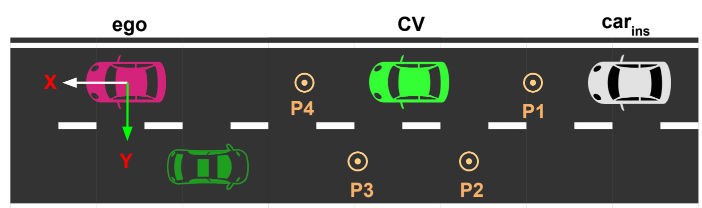

Fig. 2: overtaking

1) Constraints Applied to V2X Technology: To effectively validate V2X technology in generated scenarios, the overtaken vehicle must belong to the set of vehicles participating in cooperative perception, as defined in Constraints (8) (where V denotes the cooperative perception vehicle set). Furthermore, to ensure the smooth execution of the overtaking maneuver by car_{ins} and avoid overly brief process durations, additional constraints(9) are imposed to restrict car_{ins}' speed within a specified range.

$$car_{bo} \in V \tag{8}$$

$$car_{bo}.v \times 1.05 =< car_{ins}.v <= car_{bo}.v \times 1.5 \tag{9}$$

2) Initial Position Constraint: The vehicle being overtaken is denoted as car_{bo}, and a local coordinate system is established with its center as the origin (consistent with prior definitions). During an overtaking maneuver: car_{ins} first executes a lane change. It then accelerates to overtake car_{bo}. Finally, car_{ins} returns to its original lane. For this process, four target points P1 to P4 are designed (see Figure 2). car_{ins} sequentially navigates through these points in order, and the overtaking maneuver concludes upon reaching P4.

For the initial generation of coordinate points in overtaking behavior: The same logic and constraints as in car-following behavior (Constraints (2) and (3)) are applied. Coordinates for target points P1 to P4 are calculated as follows:

3) Constraints on Calculated Target Points: For point P1,the following constraints must be satisfied:Constraint (10) and (11): Mirror the constraints used in car-following behavior (e.g., lateral alignment and following distance limits). Constraint (12): Ensures car_{ins} maintains at least one lane width (lane.w) distance from car_{bo} when reaching P1, preventing collisions during subsequent movement toward P2.

$$P1.x < car_{bo}.x \wedge P1.y = car_{bo}.y \tag{10}$$

$$MinDistance <= |P1.x - car_{bo}.x| <= MaxDistance \tag{11}$$

$$|P1.x - car_{bo}.x| > car_{bo}.l/2 + lane.w + car_{ins}.l/2 \tag{12}$$

For point P2,the following constraints must be satisfied:Constraint (13): The position of P2 lies longitudinally between car_{bo} and P1 along the vehicle's direction of travel.Constraint (14): At P2, the front bumper of car_{ins} does not exceed the rear bumper of car_{bo}.Constraint (15): The center-to-center distance between car_{ins} and car_{bo} at P2 equals one lane width (lane.w).

$$P1.x < P2.x < car_{bo}.x \tag{13}$$

$$|P2.x - car_{bo}.x| > car_{bo}.l/2 + car_{ins}.l/2 \tag{14}$$

$$P2.y = car_{bo}.y + lane.w, \tag{15}$$

For point P4, the constraints mirror those of P1(i.e., Constraint (11) and Constraint (12)) but require P4 to be positioned longitudinally ahead of car_{bo}.

$$P4.x > car_{bo}.x \wedge P4.y = car_{bo}.y \tag{16}$$

$$MinDistance <= |P4.x - car_{bo}.x| <= MaxDistance \tag{17}$$

$$|P4.x - car_{bf}.x| > car_{bo}.l/2 + lane.w + car_{ins}.l/2 \tag{18}$$

For point P3, the constraints mirror those of P2(i.e., Constraint (13), Constraint (14), and Constraint (15)) but require P3 to be positioned longitudinally ahead of car_{bo} and longitudinally behind P4.

$$car_{bo}.x < P3.x < P4.x \tag{19}$$

$$|P3.x - car_{bo}.x| > car_{bo}.l/2 + car_{ins}.l/2 \tag{20}$$

$$P3.y = car_{bo}.y + lane.w \tag{21}$$

4) Constraints For Approaching Target Points: During subsequent coordinate generation: Target Point Definition: Sequentially assign P1 to P4 as the current target point, denoted as tarPi.Coordinate Update Logic:X-direction Adjustment:

X-direction Adjustment(dx $>$ 0):

$$if|P_{i+1}^{W}.x - tarPj.x| < \delta, P_{i+1}^{W}.x = P_i.x$$

$$else: P_{i+1}^{L}.x = \begin{cases} P_i^L.x + dx, if P_i^L.x < tarPi.x, \\ P_i^L.x - dx, if P_i^L.x > tarPi.x, \end{cases}$$

Y-direction Adjustment(dy $>$ 0):

$$if|P_{i+1}^{W}.y - tarPj.y| < \delta, P_{i+1}^{W}.y = P_i.y$$

$$else: P_{i+1}^{L}.y = \begin{cases} P_i^L.y + dy, if P_i^L.y < tarPi.y, \\ P_i^L.y - dy, if P_i^L.y > tarPi.y, \end{cases}$$

When car_{ins} reaches a target point, it switches to the next target and continues moving toward it. The overtaking maneuver concludes upon reaching the final target point. Additionally, during the movement from P1 to P2 or P3 to P4: Time Constraints:Let t_x denote the time required for x-direction travel. Let t_y denote the time required for y-direction travel. The constraint $t_x \leq t_y$ is enforced to avoid collisions between car_{ins} and car_{bo}. Example Calculation (from P1 to P2):If | P1.x - P2.x | = $\sum_{i=1}^{n} dx_i$, then t_x = n · Δt. t_y follows the same calculation logic.