

# Safety-aware Motion Prediction with Unseen Vehicles for Autonomous Driving

Xuanchi Ren<sup>1\*</sup> Tao Yang<sup>2\*</sup> Li Erran Li<sup>3</sup> Alexandre Alahi<sup>4</sup> Qifeng Chen<sup>1</sup>  
<sup>1</sup>HKUST <sup>2</sup>Xi'an Jiaotong University <sup>3</sup>Alexa AI, Amazon <sup>4</sup>EPFL

## Abstract

Motion prediction of vehicles is critical but challenging due to the uncertainties in complex environments and the limited visibility caused by occlusions and limited sensor ranges. In this paper, we study a new task, safety-aware motion prediction with unseen vehicles for autonomous driving. Unlike the existing trajectory prediction task for seen vehicles, we aim at predicting an occupancy map that indicates the earliest time when each location can be occupied by either seen and unseen vehicles. The ability to predict unseen vehicles is critical for safety in autonomous driving. To tackle this challenging task, we propose a safety-aware deep learning model with three new loss functions to predict the earliest occupancy map. Experiments on the large-scale autonomous driving nuScenes dataset show that our proposed model significantly outperforms the state-of-the-art baselines on the safety-aware motion prediction task. To the best of our knowledge, our approach is the first one that can predict the existence of unseen vehicles in most cases. Project page at <https://github.com/xrenaa/Safety-Aware-Motion-Prediction>.

## 1. Introduction

Every year, there are more than 1 million deaths related to car accidents, and up to 94% of accidents are resulted from human errors [42]. Autonomous driving systems can potentially save hundreds of thousands of lives [4]. Critical to autonomous driving is motion prediction, which predicts surrounding traffic participants [55].

Prior work on motion prediction can be broadly classified into two approaches. The first approach predicts the future trajectories of agents. Both discriminative models [17, 49, 30, 34, 52] and generative models [57, 14, 33, 35, 11, 46] are proposed. The second approach formulates this problem as an occupancy map prediction problem [18, 23, 37, 31, 39]. These prior work rarely model safety explicitly and have difficulty predicting unseen vehicles.

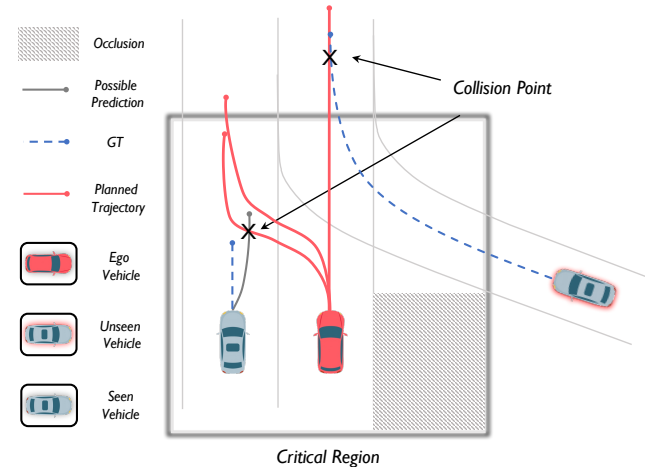


Figure 1. Our goal is to predict how early a vehicle or even unseen vehicles will occupy the space, referred to as *safety-aware motion prediction*. An unseen vehicle due to the occlusion or limited sensor ranges is the one that can not be observed by the ego vehicle in the past. Ignoring the future motion of unseen vehicles can lead to collisions. In this figure, the possible prediction (in gray) can help the planner to filter out the risky planned trajectories that may lead to collisions. Safe planning should leave a larger margin for the ego vehicle to respond.

In real-world driving scenarios, unseen vehicles are very common due to occlusions and the limited range of sensors. An *unseen vehicle* refers to a vehicle that has not appeared at present or in history but will come into view and influence planning decisions. An example of an unseen vehicle is illustrated in Figure 1. Missing the prediction of unseen vehicles threatens the safety of planning decisions and even causes collisions.

To achieve safety-first autonomous driving, we analyze the possible consequences of later/earlier prediction, *i.e.*, predicting vehicles' arrival (occupancy) time at a certain location later/earlier than the ground truth, in a specific driving scenario. As shown in Figure 1, the ground truth (GT) for the surrounding vehicle (blue car) is plotted in a blue dotted line. Due to uncertainty, it is hard to make a perfect prediction. In this case, it is safer to make a prediction earlier than the GT, *i.e.*, the predicted arrival/occupancy time at any location is earlier than GT. When we make an earlier prediction (gray line) than GT, there is a collision with

\*Equal contribution

a candidate trajectory. Though the GT trajectory actually does not have a collision with this candidate trajectory, it is safe for the planner to filter out this trajectory. Instead, if the prediction is later than GT, the planner may select a risky candidate trajectory. With the above observations, we propose the task of *safety-aware motion prediction* that includes the following two aspects:

1. For the sake of safety, the predicted occupancy time of each location should be earlier than the ground truth but as accurate as possible.
2. The prediction for unseen vehicles should be included.

To solve the proposed safety-aware motion prediction task, we propose a new representation called **earliest occupancy map** to characterize vehicles' future motion (usually in 3 to 5 seconds). The earliest occupancy map contains a value at each location indicating when this location was first occupied. To estimate the earliest occupancy map, we can formulate a regression problem with three novel loss functions. Two of the loss functions encourage accurate prediction with a preference for earlier than later predictions. The third one optimizes for unseen vehicle prediction. Moreover, with the raster image [12] as input and the earliest occupancy map as the output, we propose a new network architecture that uses a customized U-Net [38] with a dilated bottleneck and an unseen-aware self-attention unit. Our architecture takes advantage of image-to-image translation networks to model the complex motion prediction task.

Our main contributions are summarized as:

- We propose a *safety-aware motion prediction* task for autonomous driving. The task predicts the **earliest occupancy map** from surrounding vehicles, including both seen and unseen vehicles.
- We present a customized U-Net [38] architecture with a dilated bottleneck and an unseen-aware self-attention unit to obtain the earliest occupancy map. Consequently, we introduce three specific loss functions to train our model effectively.
- We introduce new evaluation metrics such as Missing Rate, Aggressiveness, and Unseen Recall to evaluate our models and baselines. The experimental results on the large-scale nuScene dataset show that our model outperforms the state-of-the-art methods for safety-aware motion prediction.

## 2. Related Work

**Motion prediction.** Accurate motion prediction is critical for autonomous driving [9, 58]. Deep learning approaches are now state-of-the-art. They have three key components, which are input representation, output representation, and models.

For the input representations, researchers propose to use either graph-based representations [19, 7, 15, 32, 41, 27, 43, 53] or rasterization-based representations [10, 2, 6, 20, 1]. Homayounfar et al. [19] propose to model the lane graph with a Directed Acyclic Graph (DAG), and Chu et al. [7] use an undirected graph to model the road layout. Djuric et al. [12] rasterize map elements (*e.g.*, roads, crosswalks) as layers and encode the lanes and vehicles with different colors. Compared with graph representation, raster maps provide richer geometric and semantic information for motion prediction [32].

For the output representation, prior work has focused on trajectories [10, 41, 6] or occupancy maps [18, 23, 37, 31, 39]. Notably, P3 [39] recently propose a semantic occupancy map to enrich the traditional occupancy map [13].

Prior work leverages either discriminative models [17, 49, 30, 34, 52] or generative models [22, 56, 16, 40, 26, 28]. Discriminative models predict either a single most-likely trajectory per agent, usually via supervised regression [6] or multiple possible trajectories using multi-modal loss function such as mixture-of-experts loss [10]. Generative models [41, 45, 29] explicitly handle multimodality by leveraging latent variable generative models, which incorporate random sampling during training and inference to capture future uncertainty. However, prior work on motion prediction does not explicitly consider safety and unseen vehicles. In this paper, we propose the earliest occupancy map as an output representation to assist autonomous driving systems for safety-aware motion prediction with unseen vehicles.

**Safety and uncertainty awareness.** Prior work on safety and uncertainty-aware autonomous driving systems has focused on uncertainty estimation [51, 3, 44, 8] and planning with collision avoidance guarantee [57, 14, 33, 35, 11, 46]. However, it is not straightforward to extend these methods to be unseen vehicles-aware. To the best of our knowledge, there are few works considering unseen vehicles for the autonomous driving system. The only exception is Tas and Stiller [46], which proposes a method to remain collision-free while considering unseen vehicles during planning. However, their method is based on hand-craft rules for each scenario considered (*e.g.* intersection crossing, give-way maneuvers) and can not generalize well to complex urban environments.

## 3. Safety-aware Motion Prediction

### 3.1. Problem Definition

Motion prediction is a necessary component for planning in autonomous driving [43]. We refer to the area in which motion prediction is needed in order for the planner of the ego vehicle to select a safe trajectory as *critical region*, which is also assumed to be larger than visible-region-with-ego-sensors. In an ideal case, the predictions for all

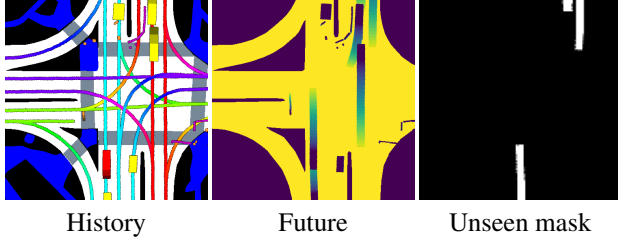


Figure 2. An example of a scene with unseen vehicles. History is represented by the raster image [12]. The ego vehicle is colored red, the other vehicles are colored yellow, and pedestrians are colored orange. Each agent’s historical polygons are colored with the same color but with a reduced level of brightness over time. Future is represented by the earliest occupancy map, where the value of each location indicates the earliest time being occupied (darker indicates a smaller value). The unseen mask indicates the locations occupied by unseen vehicles in the future.

the agents in a given scene are needed, such that the critical region is the whole scene. However, since the receptive ranges of the sensors are limited and occlusions are very common [52], we can only assume the critical region to be a neighborhood bounding box of the ego vehicle to simplify the problem. Under this circumstance, as shown in Figure 1, there is a vehicle that can not be observed by the ego vehicle at present or in history but will enter the critical region in the future and influence the decision of the planner. Furthermore, as introduced in Section 1, it is also unsafe that prediction is later than ground truth in the real world. Therefore, the *safety-aware motion prediction* is defined as predicting the **earliest occupancy map** that is earlier than the ground truth but as accurate as possible, which also takes the prediction of the unseen vehicles into consideration. We provide a more thorough problem definition in the supplementary materials.

### 3.2. Problem Formulation

Given a scene  $s$ , as assumed in Section 3.1, the critical region  $I$  is a neighbourhood bounding box of the ego vehicle to simplify the problem, *i.e.*,  $I = \{(x, y) | l \leq x \leq p, m \leq y \leq k, x, y \in \mathbb{Z}\}$ , where the center position of ego vehicle is  $(0, 0)$ . At the current time  $t$ , considering the historical motion for the previous  $H$  timesteps of the agents in the critical region  $I$  and the geometric semantic maps of the scene  $s$ , our target is to predict the future motion of all the agents of the next  $T$  timesteps, which also includes the unseen vehicles. The unseen vehicles refer to the vehicles that not in the critical region  $I$  at or before time  $t$  but enter it in future  $T$  timesteps.

**Occupancy map.** The occupancy map at time  $t$  indicates the occupancy status of each location in the critical region. Let  $B_t$  denote the set of the occupied pixels of agents in the scene at time  $t$  and  $D_t$  denote the pixels of the drivable area.

We define the occupancy map  $O_t$  at time  $t$  as follows,

$$O_t(x, y) = \begin{cases} 1, & (x, y) \in B_t \cup \overline{D_t}, \forall (x, y) \in I, \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where “overline” indicates the complement.

**Earliest occupancy map.** The earliest occupancy map indicates the timestamp that the position is first occupied. Thus, we formulate the earliest occupancy map  $E(x, y)$  as

$$E(x, y) = \min(\{\Delta t | O_{t+\Delta t}(x, y) = 1\} \cup \{T\}), \forall (x, y) \in I, \quad (2)$$

where  $t+\Delta t$  is a timestep between  $t$  and  $t+T$ . Recalling our definition in Section 3.1, our goal is to derive a prediction  $P(x, y)$  that is earlier than the ground truth  $E(x, y)$  but as accurate as possible. We formulate it by defining the hard loss (for safety) and the soft loss (for speed). We use the hard loss to penalize predictions later than the ground truth:

$$\mathcal{L}_h = \sum_{(x, y) \in I} \mathbb{1}(P(x, y) > E(x, y)). \quad (3)$$

The hard loss constrains the prediction  $P(x, y)$  to be upper bounded by ground truth  $E(x, y)$ . Only the hard loss will lead to trivial solutions, *i.e.*, all the values are zeros. We add a soft loss to make the prediction close to the ground truth. The soft loss is defined as

$$\mathcal{L}_s = - \sum_{(x, y) \in I} P(x, y). \quad (4)$$

**Unseen mask.** For the prediction of unseen vehicles, we apply an unseen vehicle loss on the predicted earliest occupancy map. We first introduce an unseen mask to make our model focus on the prediction of unseen vehicles, where the unseen mask covers all the locations occupied by any unseen vehicles in the future, as illustrated in Figure 2.

With this unseen mask  $M$ , the unseen vehicle loss is defined as follows,

$$\mathcal{L}_u = \sum_{(x, y) \in I} M(x, y) \mathbb{1}((P(x, y) > E(x, y))). \quad (5)$$

Note that the losses defined above  $\mathcal{L}_h$ ,  $\mathcal{L}_s$  and  $\mathcal{L}_u$  are for a single scene  $s$ .

## 4. Method

In this section, we introduce the technical components of our framework as shown in Figure 3.

### 4.1. Raster Image

For the input representation, we use a rasterized image of the bird’s eye view [12], as shown in Figure 2. To discuss this in more detail, the map of a scene  $s$  can be represented

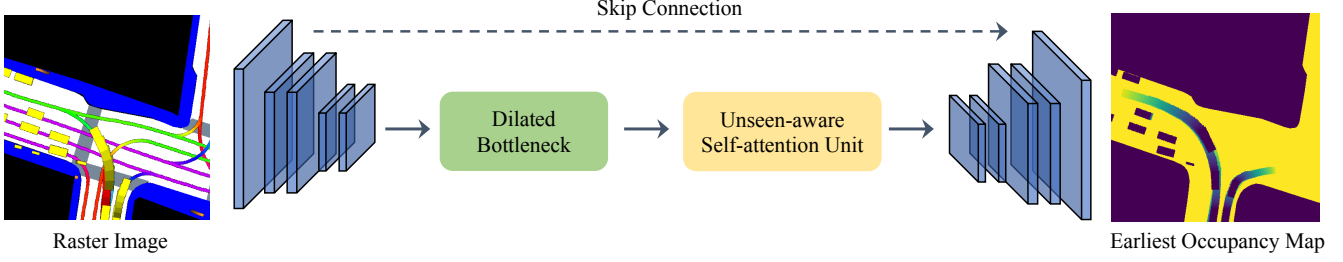


Figure 3. Overview of the proposed framework. A raster image is processed by a U-Net to generate the earliest occupancy map. Inside the U-Net, a dilated bottleneck is used to enlarge the receptive field. For the unseen vehicles, we design an unseen-aware self-attention unit.

by a raster map which includes the geometry of the road, drivable area, lane structure and direction of traffic along each lane, locations of sidewalks, and crosswalks. The bounding boxes of traffic agents at consecutive timesteps in history are rasterized on top of the map in a color fading effect to form a raster image. Furthermore, the raster image is rotated such that the ego vehicle’s heading points up. In this work, we raster the critical region, as defined in Section 3.2, as input. Here, we do not use any raw sensor data (*i.e.*, camera, LiDAR, or RaDAR) as an additional input.

#### 4.2. Dilated Bottleneck

By taking the raster image as input and the earliest occupancy map as output, the motion prediction task can be modeled as an image-to-image translation problem directly. Thus, we customized a U-Net [38] to address this problem and learn the joint distribution of the motions of different agents through the translation process. However, the lowest layer of the conventional U-Net architecture has a relatively small receptive field, which limits the network to extract only local features, *i.e.*, the model only relies on the part of the critical region to predict the motion of a vehicle, which may lead to collisions.

To enlarge the receptive field and utilize the non-local contextual information, we adopt dilated convolutions [54, 48] inside the U-Net. Dilated convolutions replace the kernels in the standard convolution layers by sparse kernels with the dilation rate, which defines a spacing between the weights in a kernel. In this way, with a dilation rate of 2, the receptive field size of a  $3 \times 3$  kernel is equal to that of a  $7 \times 7$  kernel without any increase in complexity. Thus, in the U-Net architecture, we introduce a dilated bottleneck composed of three dilated convolutions to incorporate local and global contextual information.

#### 4.3. Unseen-aware Self-Attention Unit

To make the network focus on unseen vehicles, we design a self-attention unit [47] after the dilated bottleneck. Its architecture is presented in Figure 4. The self-attention unit can encode the meaningful spatial importance on feature maps, facilitating the prediction of unseen vehicles.

Given an encoded feature map  $F \in \mathbb{R}^{h \times w \times n}$ , where  $n$

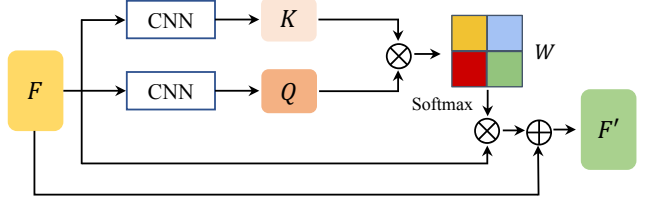


Figure 4. Illustration of the unseen-aware self-attention unit. The input feature map  $F$  is fed to two-branch CNNs to generate key  $K$  and query  $Q$ , respectively. Then we put the generated attention mask  $W$  on  $F$  and use a skip-connection to generate the final output  $F'$ .  $\otimes$  denotes element-wise product and  $\oplus$  denotes element-wise addition. The visualization for the attention mask is shown in Figure 6.

is the number of channels,  $h$  and  $w$  indicate the height and width, we feed it into two CNNs respectively to generate the query  $Q \in \mathbb{R}^{h \times w \times n}$  and the key  $K \in \mathbb{R}^{h \times w \times n}$ . Then the attention mask  $W$  is defined as

$$W_{i,j} = \frac{\exp(K_{i,j} \cdot Q_{i,j})}{\sum_{i=1}^h \sum_{j=1}^w \exp(K_{i,j} \cdot Q_{i,j})}, \quad (6)$$

where  $W_{i,j}$  indicates the importance of the feature at  $(i, j)$  for predicting unseen vehicles. In general, we observe that intersection, boundaries and historical occupied region contribute more to the feature map. We explore the design of this self-attention unit and empirically find that non-local [50] or only with one CNN branch performs worse than ours, which is presented in supplementary materials. Additionally, to aggregate the masked feature for unseen vehicles and the original feature, we adopt a skip connection inside the self-attention unit. Thus, the output  $F'$  is finally defined as

$$F' = W \times F + F. \quad (7)$$

The final output has both unseen-aware geometric and contextual information and original features, which enhances the performance of the targeting task.

#### 4.4. Learning

We train our model in an end-to-end manner. Our goal is to make a safety-aware prediction. First, we use  $\gamma_h \mathcal{L}_h + \mathcal{L}_s$



as one of the optimization objectives, where  $\gamma_h$  is a large constant serving as a loss weight. As for unseen vehicles, we use  $\mathcal{L}_u$  to supervise the learning of unseen vehicles' prediction. We thus learn the model parameters by exploiting these loss functions:

$$\mathcal{L} = \mathcal{L}_{rec} + \gamma_h \mathcal{L}_h + \mathcal{L}_s + \gamma_u \mathcal{L}_u, \quad (8)$$

where  $\mathcal{L}_h$ ,  $\mathcal{L}_s$  and  $\mathcal{L}_u$  are introduced in Section 3. Note that we calculate the average of these losses across all the scenes in dataset  $S = \{s_i\}_{i=1}^N$ . Note that the original equation of  $\mathcal{L}_h$  (Eq. 3), is not differentiable, we thus use the following equation to approximate it:

$$\mathcal{L}_h = \sum_{(x,y) \in I} \text{sigmoid}(\beta(P(x,y) - E(x,y))), \quad (9)$$

where  $\beta$  is a large constant. Similarly, we use the same approximation for  $\mathcal{L}_u$ .

To stabilize the training, we use the commonly-used pixel-wise mean squared error (MSE) function as the reconstruction term. The reconstruction loss for a single scene is

$$\mathcal{L}_{rec} = \sum_{(x,y) \in I} \|P(x,y) - E(x,y)\|^2. \quad (10)$$

## 5. Experiments

### 5.1. Baselines

We compare against the following baselines covering different types of methods:

**Physical models:** Physical models are officially provided by the nuScenes dataset [5]. There are four settings: 1) CV: the velocity is constant; 2) CA: the acceleration and heading are constant; 3) CM: the rates of change of speed and yaw are constant; 4) CY: the (scalar) speed and yaw rate are constant.

**MTP:** MTP [10] takes the raster image and the target vehicle state as input and predicts the trajectories.

**Trajectron++:** Trajectron++ [41] is a graph-structured recurrent model taking past trajectories of the agents as input to predict the future trajectories. Since it does not consider unseen vehicles in the design, we also assist Trajectron++ with a handcraft protocol to form a strong baseline: **Trajectron++\***. We use a Poisson distribution with a hyperparameter  $\lambda$  to simulate the number of unseen vehicles during the next  $T$  timesteps and put sampled unseen vehicles randomly on the boundary of the critical region at random timesteps.

**P3:** P3 [39] predicts a sequence of occupancy maps from the fused LiDAR and map features. We modify **P3** to our setting by feeding the raster image as input.

To evaluate the baselines, we convert the outputs of them to the earliest occupancy maps. For **Physical models**, **MTP**

and **Trajectron++**, we fit splines on the predicted trajectories and get the yaw to convert the trajectories to the earliest occupancy map. For **P3**, we convert the predicted sequence of occupancy maps to the earliest occupancy map, as defined in Eq. 2.

### 5.2. Metrics

To evaluate the performance of our model, we use a common **MSE** metric and design three metrics to evaluate safety-aware motion prediction from different aspects. We introduce the metrics below.

**Missing Rate (MR).** For safety, a later prediction is intolerable. Missing Rate indicates the percentage of the predicted earliest occupancy map that is later than the ground truth. For  $s \in S$ , given a predicted earliest occupancy map  $P$  and the corresponding ground truth  $E$ , the Missing Rate can be defined as

$$\text{MR} = \frac{\sum_{s \in S} \sum_{(x,y) \in I_s} \mathbb{1}(P^s(x,y) > E^s(x,y))}{\sum_{s \in S} |I_s|}. \quad (11)$$

**Aggressiveness.** The trivial solution for safety-aware motion prediction is that all the cars in the scene  $s$  are keeping still. In this case, the values of the earliest occupancy map will be zero. However, this is undesirable. Thus, we use the Aggressiveness metric to evaluate if the model has trivial solutions. Given predicted earliest occupancy maps  $P$ , this metric is defined as

$$\text{Aggressiveness} = \frac{\sum_{s \in S} \sum_{(x,y) \in \hat{I}_s} (C - P^s(x,y))}{\sum_{s \in S} |\hat{I}_s|}, \quad (12)$$

where  $\hat{I}_s$  is the subset of  $I_s$  containing coordinates that subject to  $E^s(x,y) \neq 0$ , *i.e.*,  $\hat{I}_s = \{(x,y) | (x,y) \in I_s, \text{ s.t. } E^s(x,y) \neq 0\}$ , and  $C$  is a constant to make the value of the metric positive.

**Unseen Recall (UR).** To evaluate the ability of the model to capture unseen vehicles, we choose to calculate the recall for the prediction of unseen vehicles. Given the unseen mask  $M$ , the set of occupied positions of the unseen vehicles is  $\hat{M} = \{(x,y) | M(x,y) = 1\}$ , the IoU for unseen vehicles is defined as

$$\text{IoU} = \frac{|\hat{M} \cap \hat{P}|}{|\hat{M}|}, \quad (13)$$

where  $\hat{P}$  is the set of positions of the predicted motions, *i.e.*,  $\hat{P} = \{(x,y) | t < P(x,y) < t + T\}$ . Then Unseen Recall (UR) is defined as:

$$\text{UR}_\alpha = \frac{\sum_{s \in \hat{S}} \mathbb{1}(\text{IoU}_s > \alpha)}{|\hat{S}|}, \quad (14)$$

where  $\hat{S}$  are the subset of  $S$  that containing unseen vehicles. Here, we consider the threshold  $\alpha$  to be 0.3, 0.5 and 0.7.

Method	MR (%) ↓	Aggressiveness ↓	UR <sub>0.3</sub> (%) ↑	UR <sub>0.5</sub> (%) ↑	UR <sub>0.7</sub> (%) ↑	MSE ↓
Physical-CV	6.53	2.77	10.98	4.58	1.46	26.26
Physical-CA	6.39	2.82	11.54	4.91	1.53	26.75
Physical-CM	6.36	2.86	11.47	4.52	1.43	26.19
Physical-CY	6.48	2.81	10.95	4.39	1.43	25.89
MTP	6.41	2.39	7.38	2.14	0.55	20.46
Trajectron++	8.93	<b>1.71</b>	20.40	9.33	3.45	15.38
Trajectron++*	8.97	1.80	20.98	9.36	3.48	15.99
P3	6.78	2.66	12.12	1.72	0.12	13.18
Ours	<b>1.37</b>	2.48	<b>63.28</b>	<b>43.48</b>	<b>18.85</b>	<b>10.61</b>

Table 1. Safety-aware motion prediction performance quantitative comparison on the **nuScenes** dataset. Bold indicates best.

Method	MR (%) ↓	Aggressiveness ↓	UR <sub>0.3</sub> (%) ↑	UR <sub>0.5</sub> (%) ↑	UR <sub>0.7</sub> (%) ↑	MSE ↓
MTP	8.84	5.67	51.25	8.83	0.74	77.94
P3	9.20	<b>1.48</b>	2.76	0.24	0.00	28.54
Ours	<b>3.97</b>	3.55	<b>88.81</b>	<b>80.22</b>	<b>30.48</b>	<b>18.30</b>

Table 2. Safety-aware motion prediction performance quantitative comparison on the **Lyft** dataset. Bold indicates best.

**MSE.** To evaluate the performance of motion prediction models, Average Displacement Error (ADE) [16] is commonly used. Due to the output occupancy map of our method is image-level, we use the MSE metric between the prediction and GT instead to evaluate the accuracy of the predictions. Note that MSE is only used as a reference.

### 5.3. Implementation details

Our model is implemented in Pytorch [36] and trained on an NVIDIA V100 GPU in around 24 hours. We used a batch size of 32 and trained with Adam optimizer [24] with a learning rate to  $1 \times 10^{-4}$ .

The critical region used in our work is of size 50 meters by 50 meters. The range in front of the ego vehicle is 40 meters, and the range at the back is 10 meters. The ranges for the left and the right are the same, which are both 25 meters. The pixel resolution of the raster image is 1:10. Thus,  $m = -100, k = 400, l = -250, p = 250$ . For all the models, we only feed the agents inside the critical region at present and in history. For the Poisson distribution using the handcrafted protocol, we use a  $\lambda = 2$ .

For the hyper-parameters, we use the information from the past 2 seconds to predict the future 3 seconds. Thus, with a frequency of 10 Hz, the total number of the historical timesteps  $H$  is 20, and the future timesteps  $T$  is 30. The data provided by the nuScenes dataset is 2 Hz, so we interpolate it to 10 Hz<sup>1</sup> to make the earliest occupancy map smooth. Considering  $T = 30$ , we set  $C = 31$ . For the loss functions, we set  $\beta = 100$  and  $\gamma_h = \gamma_u = 1000$ . The dilated rates used in the dilated bottleneck are 2, 4, and 8, respectively.

<sup>1</sup>For the input raster image, we only use 2 Hz data.

### 5.4. Evaluation on the nuScenes dataset

We evaluate our method on the public nuScenes dataset [5]. It is a large-scale dataset for autonomous driving with 1000 scenes in Boston and Singapore. Each scene is annotated at 2 Hz and is 20s long, containing up to 23 semantic object classes, as well as high definition maps with 11 annotated layers. We follow the official benchmark for the nuScenes prediction challenge to split the dataset. There are 32,186 prediction scenes in the training set and 8,560 scenes in the validation set. Due to the inaccessible ground truth of the test set, we use the validation set to evaluate the models for safety-aware prediction.

To understand the prevalence of unseen vehicles, we compute the number of scenes with unseen vehicles in the nuScenes dataset when the critical region is limited to be 50 meters by 50 meters. There are about 47% of scenes containing unseen vehicles in the training set and about 32% of scenes in the validation set. This indicates that unseen vehicles are common in real-world scenarios.

**Quantitative Comparison.** We perform the quantitative comparison on the baselines and our model in terms of the above four metrics. Since the baselines do not consider unseen vehicles, to illustrate the effectiveness of our method, we modify Trajectron++ to Trajectron++\* with a handcrafted unseen vehicle prediction protocol. The results are summarized in Table 1. By modeling safety-aware prediction explicitly and using the earliest occupancy map as representation, our model outperforms the state-of-the-art models and traditional physical models except on Aggressiveness. However, note that the Aggressiveness metric evaluates if the models have trivial solutions. Therefore,

Method	MR (%) ↓	Aggressiveness ↓	UR <sub>0.3</sub> (%) ↑	UR <sub>0.5</sub> (%) ↑	UR <sub>0.7</sub> (%) ↑	MSE ↓
Ours w/o $\mathcal{L}_h$	18.00	<b>1.39</b>	36.98	20.73	6.76	6.55
Ours w/o $\mathcal{L}_s$	5.85	3.53	46.31	26.36	9.91	10.76
Ours w/o $\mathcal{L}_u$	6.60	2.47	49.78	29.89	10.36	<b>6.53</b>
Ours w/o Attention	5.66	2.65	39.97	22.00	6.79	6.91
Ours	<b>1.37</b>	2.48	<b>63.28</b>	<b>43.48</b>	<b>18.85</b>	10.61

Table 3. Ablation study for proposed loss and module.

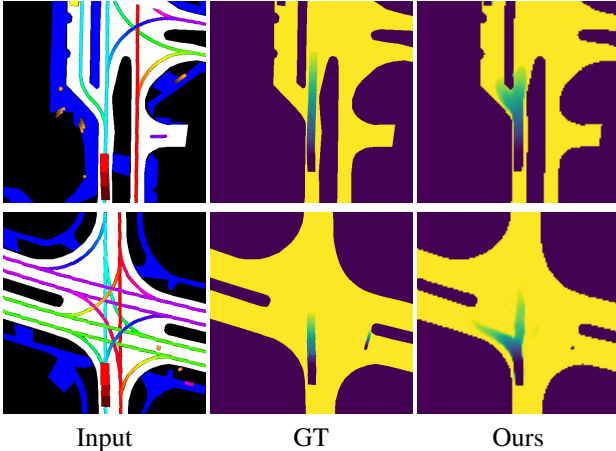


Figure 5. Multi-modal predictions made by our method. Using the earliest occupancy map, we can achieve multi-modal future predictions without taking an explicit probabilistic approach.

it is not an essential metric for safety-aware prediction. We can observe that our model has the minimum MR and MSE, which indicates that our model has the fewest cases that prediction is later than ground truth and conforms to the definition for safety-aware prediction: earlier but as accurate as possible. UR measures if the models can predict the unseen vehicles without omission. Our model achieves the highest recall across different thresholds, indicating that it can predict unseen vehicles effectively. Note that a hand-crafted protocol can not help a lot for unseen vehicle prediction, demonstrating that the prediction for unseen vehicles should take contextual information into consideration. Furthermore, the deep learning-based baselines do not outperform physical-based methods significantly.

**Qualitative Comparison.** We show our prediction results under diverse traffic scenarios and provide some representative comparisons with the deep learning-based baselines in Figure 7. Please refer to supplementary materials for more results.

**Visualization for attention map.** We formulate the motion prediction problem as an image-to-image translation problem and train our model with input-output image pairs. Therefore, the prediction for unseen vehicles relies on the data distribution, especially the density of agents and entrance locations. To understand the mechanism of the unseen-aware self-attention unit, we visualize the spatial at-

tention maps by overlaying them on the input images in Figure 6. We can observe that spatial attention helps our model locate the unseen vehicles and drivable regions, which indicates that our model learns the patterns of the data, particularly for the unseen vehicles.

**Multi-modality.** Multi-modality gain popularity recently in motion prediction. Instead of using probabilistic approaches, we provide an alternative way by using the earliest occupancy map. As shown in Figure 5, with our proposed formulation and loss, the earliest occupancy map is capable of representing multi-modal predicted motion in a single output. Furthermore, as shown in Figure 7, the motions predicted by our method tend to have a bit larger range and makes the system safety-awareness. For future work, a hierarchical probabilistic U-Net [25] may further improve the ability for multi-modal prediction.

## 5.5. Evaluation on the Lyft Dataset

In this section, we further evaluate our model on the Lyft dataset. The Lyft dataset [21] has over 1,000 hours of driving data in Palo Alto, California. It consists of 170,000 scenes, each of which is 25 seconds long. It also provides a high-definition semantic map with 15,242 labeled elements. We follow the official guidelines of the Kaggle challenge to split the dataset. There are 4,009,980 prediction scenes in the training set. For the validation, we use 20,000 scenes, a subset of the official validation set.

Because of the lack of support for the Lyft dataset of the state-of-the-art methods, we only select MTP [10] and P3 [39] as the baselines to compare in terms of the above four metrics. The results are summarized in Table 2. Compared to baselines, our method achieves the best MR, UR, and MSE, which shows that our model predictions are safe and accurate. Our method to detect unseen vehicles relies on the current frame; however, there are many missing frames for agents in the Lyft dataset, which results in more detected unseen vehicles.

## 5.6. Ablation studies

To develop an understanding of which model component influences the performance, we conduct ablation studies on the proposed losses and attention module on the nuScenes dataset. The results are summarized in Table 3. We have three key observations. 1) The hard loss is essential for

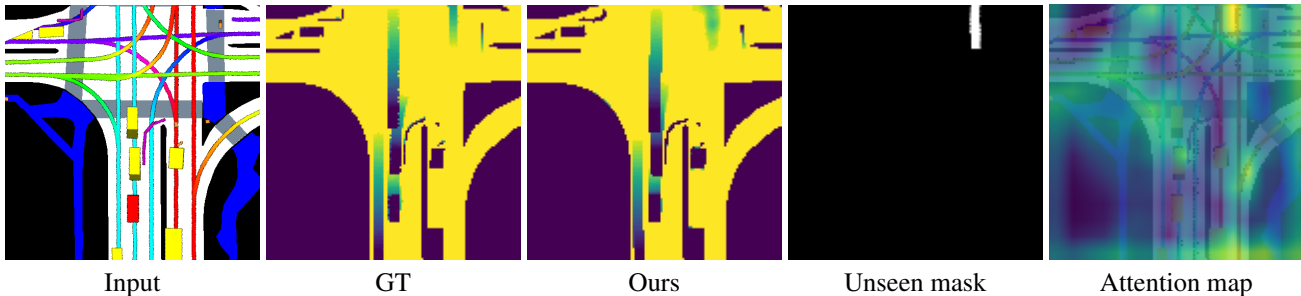


Figure 6. Visualization of attention masks  $W$ . For the attention map, the brighter area in the image indicates more significant responses. The attention map has higher responses around the unseen mask, thereby helping the model predict the motion of unseen vehicles.

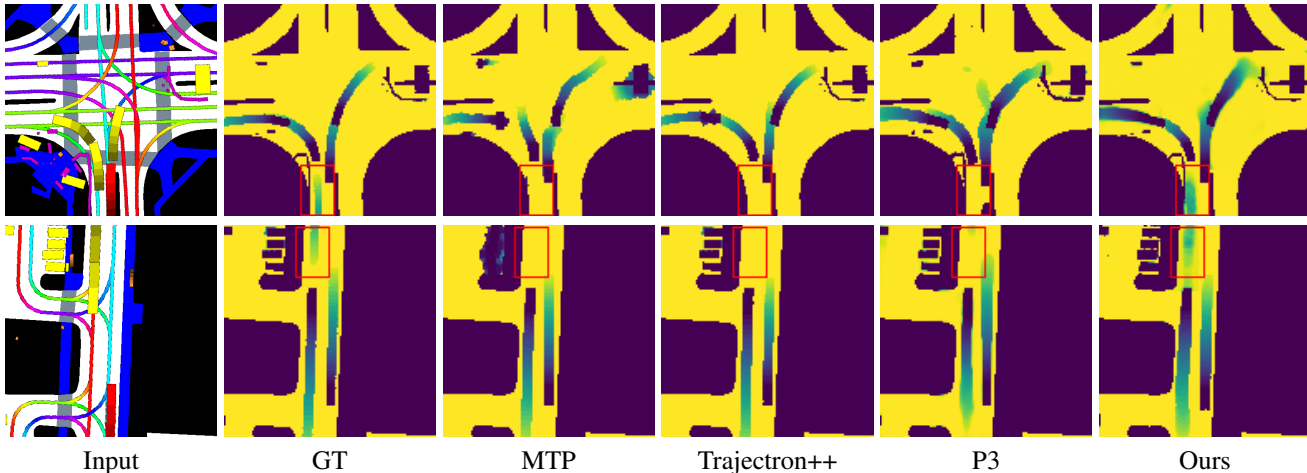


Figure 7. Visual comparisons between ours and other baselines on the nuScenes dataset. All the prediction results are visualized with the earliest occupancy maps. The unseen vehicles are annotated with red bounding boxes. We show common failures of the baselines, including missing predictions for unseen vehicles and later predictions for seen vehicles. Such unsafe predictions could mislead the ego vehicle to make poor planning decisions. In contrast, the future motion predicted by our method is earlier but as accurate as possible and includes unseen vehicles.

safety-aware prediction. The first row shows that training our model without hard loss results in a significant drop in the MR and UR. 2) The unseen loss, soft loss, and unseen-aware self-attention unit are necessary components for our model. Lacking any one of them hurts the performance in terms of MR and UR. 3) As one would expect, the unseen-aware self-attention unit is more important for learning the prediction of unseen vehicles than other components. Even without the unseen loss as supervision, our method can still outperform the baselines for predicting unseen vehicles.

Note that, without hard loss, the soft loss is adequately optimized. Therefore, “Ours w/o hard” achieves the lowest aggressiveness, but it does not mean that it is safer than others. The slight drop in the MSE of the final model is due to the wrong prediction of unseen vehicles (false positive). Overall, the hard loss and unseen-aware self-attention unit are the dominant performance-improving components.

## 6. Conclusion

In this paper, we study a new task named safety-aware motion prediction for autonomous driving. The proposed

task requires the predicted event (arrival time at a location) to be earlier than the actual event in the future while as accurate as possible. We introduce a novel safety-aware representation called the earliest occupancy map that characterizes the vehicles’ future motion. With this representation, we formulate the safety-aware motion prediction as an image-to-image translation problem. To solve the problem, we present a customized U-Net architecture with a dilated bottleneck to enlarge the receptive field and an unseen-aware self-attention unit to facilitate the prediction of unseen vehicles. Our model is trained effectively with three novel loss functions. Experimental results on a large-scale autonomous-driving dataset show that the proposed framework significantly outperforms state-of-the-art baselines on the safety-aware motion prediction task. As for the limitation, our method may have some false positive predictions for the unseen vehicles. Though the false positives do not compromise the safety, they may introduce more constraints for the planner.



## References

- [1] Mohammadhossein Bahari, Nejjar Ismail, and Alexandre Alahi. Injecting knowledge in data-driven vehicle trajectory predictors. *Transportation Research Part C*, 2021. 2
- [2] Mayank Bansal, Alex Krizhevsky, and Abhijit Ogale. Chauffeurnet: Learning to drive by imitating the best and synthesizing the worst. *arXiv preprint arXiv:1812.03079*, 2018. 2
- [3] Adam Berthelot, Andreas Tamke, Thao Dang, and Gabi Breuel. A novel approach for the probabilistic computation of time-to-collision. In *IV*, 2012. 2
- [4] Lawrence Blincoe, Ted R Miller, Eduard Zaloshnja, and Bruce A Lawrence. The economic and societal impact of motor vehicle crashes, 2010. Technical report, 2015. 1
- [5] Holger Caesar, Varun Bankiti, Alex H. Lang, Sourabh Vora, Venice Erin Liong, Qiang Xu, Anush Krishnan, Yu Pan, Giancarlo Baldan, and Oscar Beijbom. nuscenes: A multimodal dataset for autonomous driving. *arXiv preprint arXiv:1903.11027*, 2019. 5, 6
- [6] Yuning Chai, Benjamin Sapp, Mayank Bansal, and Dragomir Anguelov. Multipath: Multiple probabilistic anchor trajectory hypotheses for behavior prediction. In *CoRL*, 2019. 2
- [7] Hang Chu, Daiqing Li, David Acuna, Amlan Kar, Maria Shugrina, Xinkai Wei, Ming-Yu Liu, Antonio Torralba, and Sanja Fidler. Neural turtle graphics for modeling city road layouts. In *ICCV*, 2019. 2
- [8] Alexandre Constantin, Junghee Park, and Karl Iagnemma. A margin-based approach to threat assessment for autonomous highway navigation. In *IV*, 2014. 2
- [9] Akansel Cosgun, Lichao Ma, Jimmy Chiu, Jiawei Huang, Mahmut Demir, Alexandre Miranda Anon, Thang Lian, Hasan Tafish, and Samir Al-Stouhi. Towards full automated drive in urban environments: A demonstration in gomentum station, california. In *IV*, 2017. 2
- [10] Henggang Cui, Vladan Radosavljevic, Fang-Chieh Chou, Tsung-Han Lin, Thi Nguyen, Tzu-Kuo Huang, Jeff Schneider, and Nemanja Djuric. Multimodal trajectory predictions for autonomous driving using deep convolutional networks. In *ICRA*, 2019. 2, 5, 7
- [11] Wenchao Ding, Lu Zhang, Jing Chen, and Shaojie Shen. Safe trajectory generation for complex urban environments using spatio-temporal semantic corridor. *RA-L*, 2019. 1, 2
- [12] Nemanja Djuric, Vladan Radosavljevic, Henggang Cui, Thi Nguyen, Fang-Chieh Chou, Tsung-Han Lin, Nitin Singh, and Jeff Schneider. Uncertainty-aware short-term motion prediction of traffic actors for autonomous driving. In *WACV*, 2020. 2, 3
- [13] Alberto Elfes. Using occupancy grids for mobile robot perception and navigation. *Computer*, 1989. 2
- [14] Stephen M Erlien, Susumu Fujita, and J Christian Gerdes. Safe driving envelopes for shared control of ground vehicles. *IFAC Proceedings Volumes*, 2013. 1, 2
- [15] Jiyang Gao, Chen Sun, Hang Zhao, Yi Shen, Dragomir Anguelov, Congcong Li, and Cordelia Schmid. Vectornet: Encoding hd maps and agent dynamics from vectorized representation. In *CVPR*, 2020. 2
- [16] Agrim Gupta, Justin Johnson, Li Fei-Fei, Silvio Savarese, and Alexandre Alahi. Social gan: Socially acceptable trajectories with generative adversarial networks. In *CVPR*, 2018. 2, 6
- [17] Dirk Helbing and Peter Molnar. Social force model for pedestrian dynamics. *Physical review E*, 1995. 1, 2
- [18] Stefan Hoermann, Martin Bach, and Klaus Dietmayer. Dynamic occupancy grid prediction for urban autonomous driving: A deep learning approach with fully automatic labeling. In *ICRA*, 2018. 1, 2
- [19] Namdar Homayounfar, Wei-Chiu Ma, Justin Liang, Xinyu Wu, Jack Fan, and Raquel Urtasun. Dagmapper: Learning to map by discovering lane topology. In *ICCV*, 2019. 2
- [20] Joey Hong, Benjamin Sapp, and James Philbin. Rules of the road: Predicting driving behavior with a convolutional model of semantic interactions. In *CVPR*, 2019. 2
- [21] John Houston, Guido Zuidhof, Luca Bergamini, Yawei Ye, Ashesh Jain, Sammy Omari, Vladimir Iglovikov, and Peter Ondruska. One thousand and one hours: Self-driving motion prediction dataset. In *CoRL*, 2020. 7
- [22] Boris Ivanovic and Marco Pavone. The trajectron: Probabilistic multi-agent trajectory modeling with dynamic spatiotemporal graphs. In *ICCV*, 2019. 2
- [23] Ajay Jain, Sergio Casas, Renjie Liao, Yuwen Xiong, Song Feng, Sean Segal, and Raquel Urtasun. Discrete residual flow for probabilistic pedestrian behavior prediction. In *CoPR*, 2020. 1, 2
- [24] Diederik P. Kingma and Jimmy Ba. Adam: A method for stochastic optimization. In Yoshua Bengio and Yann LeCun, editors, *ICLR*, 2015. 6
- [25] Simon A. A. Kohl, Bernardino Romera-Paredes, Klaus H. Maier-Hein, Danilo Jimenez Rezende, S. M. Ali Eslami, Pushmeet Kohli, Andrew Zisserman, and Olaf Ronneberger. A hierarchical probabilistic u-net for modeling multi-scale ambiguities. *CoRR*, abs/1905.13077, 2019. 7
- [26] Vineet Kosaraju, Amir Sadeghian, Roberto Martín-Martín, Ian Reid, S Hamid Rezafofighi, and Silvio Savarese. Socialbigat: Multimodal trajectory forecasting using bicycle-gan and graph attention networks. *arXiv preprint arXiv:1907.03395*, 2019. 2
- [27] Parth Kothari, Sven Kreiss, and Alexandre Alahi. Human trajectory forecasting: A deep learning perspective. *IEEE Transactions on Intelligent Transportation Systems*, 2021. 2
- [28] Parth Kothari, Brian Siffringer, and Alexandre Alahi. Interpretable social anchors for human trajectory forecasting in crowds. In *CVPR*, 2021. 2
- [29] Namhoon Lee, Wongun Choi, Paul Vernaza, Christopher B. Choy, Philip H. S. Torr, and Manmohan Chandraker. Desire: Distant future prediction in dynamic scenes with interacting agents. In *CVPR*, 2017. 2
- [30] Namhoon Lee and Kris M Kitani. Predicting wide receiver trajectories in american football. In *WACV*, 2016. 1, 2
- [31] Junwei Liang, Lu Jiang, Kevin Murphy, Ting Yu, and Alexander Hauptmann. The garden of forking paths: Towards multi-future trajectory prediction. In *CVPR*, 2020. 1, 2

- [32] Ming Liang, Bin Yang, Rui Hu, Yun Chen, Renjie Liao, Song Feng, and Raquel Urtasun. Learning lane graph representations for motion forecasting. In *ECCV*, 2020. 2
- [33] Changliu Liu, Chung-Yen Lin, and Masayoshi Tomizuka. The convex feasible set algorithm for real time optimization in motion planning. *SIAM Journal on Control and optimization*, 2018. 1, 2
- [34] Jeremy Morton, Tim A Wheeler, and Mykel J Kochenderfer. Analysis of recurrent neural networks for probabilistic modeling of driver behavior. *T-ITS*, 2016. 1, 2
- [35] Maximilian Naumann, Hendrik Konigshof, Martin Lauer, and Christoph Stiller. Safe but not overcautious motion planning under occlusions and limited sensor range. In *IV*, 2019. 1, 2
- [36] Adam Paszke, Sam Gross, Soumith Chintala, Gregory Chanan, Edward Yang, Zachary DeVito, Zeming Lin, Alban Desmaison, Luca Antiga, and Adam Lerer. Automatic differentiation in pytorch. 2017. 6
- [37] Daniela Ridet, Nachiket Deo, Denis Wolf, and Mohan Trivedi. Scene compliant trajectory forecast with agent-centric spatio-temporal grids. *RA-L*, 2020. 1, 2
- [38] Olaf Ronneberger, Philipp Fischer, and Thomas Brox. U-net: Convolutional networks for biomedical image segmentation. In *MICCAI*, 2015. 2, 4
- [39] Abbas Sadat, Sergio Casas, Mengye Ren, Xinyu Wu, Pranaab Dhawan, and Raquel Urtasun. Perceive, predict, and plan: Safe motion planning through interpretable semantic representations. In *ECCV*, 2020. 1, 2, 5, 7
- [40] Amir Sadeghian, Vineet Kosaraju, Ali Sadeghian, Noriaki Hirose, Hamid Rezaatofghi, and Silvio Savarese. Sophie: An attentive gan for predicting paths compliant to social and physical constraints. In *CVPR*, 2019. 2
- [41] Tim Salzmann, Boris Ivanovic, Punarjay Chakravarty, and Marco Pavone. Trajectron++: Dynamically-feasible trajectory forecasting with heterogeneous data. In *ECCV*, 2020. 2, 5
- [42] Santokh Singh. Critical reasons for crashes investigated in the national motor vehicle crash causation survey. Technical report, 2015. 1
- [43] Haoran Song, Wenchao Ding, Yuxuan Chen, Shaojie Shen, Michael Yu Wang, and Qifeng Chen. Pip: Planning-informed trajectory prediction for autonomous driving. In *ECCV*, 2020. 2
- [44] Jan Erik Stellet, Jan Schumacher, Wolfgang Branz, and J Marius Zöllner. Uncertainty propagation in criticality measures for driver assistance. In *IV*, 2015. 2
- [45] Yichuan Charlie Tang and Ruslan Salakhutdinov. Multiple futures prediction. 2019. 2
- [46] Ömer Şahin Taş and Christoph Stiller. Limited visibility and uncertainty aware motion planning for automated driving. In *IV*, 2018. 1, 2
- [47] Ashish Vaswani, Noam Shazeer, Niki Parmar, Jakob Uszkoreit, Llion Jones, Aidan N. Gomez, Lukasz Kaiser, and Illia Polosukhin. Attention is all you need. In *NeurIPS*, 2017. 4
- [48] Sulaiman Vesal, Nishant Ravikumar, and Andreas K. Maier. A 2d dilated residual u-net for multi-organ segmentation in thoracic CT. In *SegTHOR@ISBI*, 2019. 4
- [49] Jack M Wang, David J Fleet, and Aaron Hertzmann. Gaussian process dynamical models for human motion. *TPAMI*, 2007. 1, 2
- [50] Xiaolong Wang, Ross B. Girshick, Abhinav Gupta, and Kaiming He. Non-local neural networks. In *CVPR*, 2018. 4
- [51] Michael T Wolf and Joel W Burdick. Artificial potential functions for highway driving with collision avoidance. In *ICRA*, 2008. 2
- [52] Tao Yang, Zhixiong Nan, He Zhang, Shitao Chen, and Nanning Zheng. Traffic agent trajectory prediction using social convolution and attention mechanism. In *IV*, 2020. 1, 2, 3
- [53] Maosheng Ye, Tongyi Cao, , and Qifeng Chen. Tpcn: Temporal point cloud networks for motion forecasting. In *CVPR*, 2021. 2
- [54] Fisher Yu and Vladlen Koltun. Multi-scale context aggregation by dilated convolutions. In *ICLR*, 2016. 4
- [55] Wei Zhan, Arnaud de La Fortelle, Yi-Ting Chen, Ching-Yao Chan, and Masayoshi Tomizuka. Probabilistic prediction from planning perspective: Problem formulation, representation simplification and evaluation metric. In *IV*, 2018. 1
- [56] Tianyang Zhao, Yifei Xu, Mathew Monfort, Wongun Choi, Chris Baker, Yibiao Zhao, Yizhou Wang, and Ying Nian Wu. Multi-agent tensor fusion for contextual trajectory prediction. In *CVPR*, 2019. 2
- [57] Zhijie Zhu, Edward Schmerling, and Marco Pavone. A convex optimization approach to smooth trajectories for motion planning with car-like robots. In *CDC*, 2015. 1, 2
- [58] Julius Ziegler, Philipp Bender, Markus Schreiber, Henning Lategahn, Tobias Strauss, Christoph Stiller, Thao Dang, Uwe Franke, Nils Appenrodt, Christoph G Keller, et al. Making bertha drive—an autonomous journey on a historic route. *IEEE Intelligent transportation systems magazine*, 2014. 2