Masked Autoencoders for Self-Supervised Learning on Automotive Point Clouds

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Abstract

Masked autoencoding has become a successful pre-training paradigm for Transformer models for text, images, and recently, point clouds. Raw automotive datasets are a suitable candidate for self-supervised pre-training as they generally are cheap to collect compared to annotations for tasks like 3D object detection (OD). However, development of masked autoencoders for point clouds has focused solely on synthetic and indoor data. Consequently, existing methods have tailored their representations and models toward point clouds which are small, dense and have homogeneous point density. In this work, we study masked autoencoding for point clouds in an automotive setting, which are sparse and for which the point density can vary drastically among objects in the same scene. To this end, we propose Voxel-MAE, a simple masked autoencoding pre-training scheme designed for voxel representations. We pre-train the backbone of a Transformer-based 3D object detector to reconstruct masked voxels and to distinguish between empty and non-empty voxels. Our method improves the 3D OD performance by 1.75 mAP points and 1.05 NDS on the challenging nuScenes dataset. Compared to existing self-supervised methods for automotive data, Voxel-MAE displays up to a $2\times$ performance increase. Further, we show that by pre-training with Voxel-MAE, we require only 40% of the annotated data to outperform a randomly initialized equivalent. Code will be released.

1. Introduction

Self-supervised learning enables the extraction of rich features from data without the need for human annotations. This has opened up new avenues where models can be trained on ever-larger datasets. Fueled by robust representations, self-supervised models have seen great success in fields such as Natural Language Processing (NLP) \cite{devlin2018bert, radford2019language, brown2020language} and computer vision \cite{devlin2018bert, dosovitskiy2021an,touvron2021deit}. Specifically, masked language modeling \cite{radford2019language} and masked image modeling \cite{devlin2018bert, dosovitskiy2021an, touvron2021deit} have proven themselves as simple, yet effective, pre-training strategies. Both of these approaches train models to reconstruct sentences, or images, from partially masked inputs. Subsequently, models can be fine-tuned toward downstream tasks, often outperforming their fully supervised equivalents.

Autonomous driving is an application well suited for self-supervised pre-training strategies, including masked autoencoding. In the automotive domain, the collection of raw data is relatively cheap, while annotations for common tasks such as object detection (OD), tracking or semantic

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{MAE \cite{heo2020masked} (left) divides images into non-overlapping patches of fixed size. Existing methods (middle) for masked point modeling create point cloud patches with a fixed number of points by using furthest point sampling and k-nearest neighbors. Our method (right) uses non-overlapping voxels with a dynamic number of points. Airplane point cloud from \cite{milioto2019nuscenes}.}
\end{figure}
segmentation are expensive and time-consuming to acquire. Especially for data in 3D, the sparsity of lidar and radar sensors can make labeling labor intensive and even ambiguous. Self-supervised pre-training is thus an appealing alternative to create robust and general feature representations, and ultimately reduce the need for human-annotated data.

Recently, multiple works have applied masked point modeling techniques to pre-train point cloud encoders [16, 22, 27, 37, 39]. These have achieved favorable results on downstream tasks like shape classification, shape segmentation, few-shot classification, and indoor 3D OD, indicating the effectiveness of masked autoencoders in the point cloud domain. However, evaluation has been focused only on synthetic data such as ShapeNet [6] and ModelNet40 [35], and indoor datasets like ScanObjectNN [33], ScanNet [10], and SUN RGB-D [30]. Compared to automotive point clouds, these datasets contain many points for all objects and the point density is more even throughout the scene, making the detection and classification of objects less challenging.

Naturally, design choices like point cloud representation and model selection have been tailored toward dataset characteristics. For instance, the low number of points per scene lessens requirements on computational efficiency and has enabled the use of vanilla Transformers [22, 27, 37]. Further, existing methods have relied exclusively on furthest point sampling (FPS) and k-nearest neighbors (kNN) for representing point clouds and dividing them into subsets of equally many points, see Fig. 1. This works well when point clouds are evenly distributed and it simplifies the reconstruction during pre-training as the model predicts a fixed number of points for each subset. However, this representation is sub-optimal for efficiently solving downstream tasks in certain domains. First, there is a risk of discarding points, as shown at the wing tips in Fig. 1. This potential loss of information makes it unsuitable for safety-critical domains. Second, the representation is redundant as subsets may overlap, creating unnecessary computational load.

In this work, we propose to use masked point modeling in an automotive setting. To this end, we present Voxel-MAE, a masked autoencoder pre-training for voxelized point clouds, and deploy it on the large-scale automotive dataset nuScenes [4] to study its effects on 3D OD. We use dynamic voxelization [41] to handle an arbitrary number of points per voxel and to get a dense point cloud representation suitable for the downstream task of 3D OD. Further, we use the Single-stride Sparse Transformer (SST) [14] as our point cloud encoder, which applies a shifted-window transformer directly to the voxelized point cloud, similar to the Swin Transformer for images [24]. The Transformer-based backbone is chosen for masked autoencoding as its pre-training scales favorably when deploying extensive masking, where only unmasked data is embedded in the encoder. Further, the model efficiently handles the sparseness of point cloud data by only processing non-empty voxels. Last, SST has achieved competitive results for 3D object detection, capturing fine details while being computationally efficient, making it a strong baseline.

For the pre-training, we follow the training paradigm of MAE [18] and equip the model with a lightweight decoder used for reconstructing masked input. Unlike previous approaches such as Point-BERT [57] and POS-BERT [16], our method is simple and does not rely on training a separate tokenizer for embedding and reconstructing the point cloud. Instead, our method directly predicts the masked voxelized point clouds. To handle the uneven point cloud density and sparsity of lidar point clouds we use a novel combination of pre-training tasks.

Our contributions are the following:

- We propose Voxel-MAE, a method for deploying MAE-style pre-training on voxelized point clouds and evaluate it on nuScenes, a large-scale automotive point cloud dataset.
- Our method is data-efficient and reduces the need for annotated data, outperforming its fully-supervised equivalent when using only 40% of the annotated data.
- Voxel-MAE boosts the performance of a transformer-based detector by 1.75%-points in mAP and 1.05%-points in NDS, showcasing up to 2× the performance increase compared to existing self-supervised methods.

### 2. Related Work

**Masked autoencoders for language and images.** Masked language modeling (MLM) and its derivatives such as BERT [11] and GPT [3, 28, 29] have been very successful within NLP. These methods learn data representations by masking part of an input sentence and train models to predict the missing parts. The methods scale well, enabling training on datasets of unprecedented size and their representations generalize to various downstream tasks. Inspired by their success, multiple methods have applied similar techniques to the image domain [2, 7, 12, 18, 36]. Recently, the authors of [18] proposed MAE, a simple approach where random image patches are masked and their pixel values are used as reconstruction targets. Further, they deploy an asymmetric encoder-decoder architecture, where only visible patches are embedded by the encoder, and a lightweight decoder is used for reconstruction. MAE is shown to improve performance on a range of downstream tasks compared to a fully supervised baseline. Voxel-MAE follows this design philosophy and makes the non-trivial translation to sparse point cloud data.

**Masked autoencoders for point clouds.** Inspired by the success of MLM in NLP and MAE in computer vision,
multiple adaptations to the point cloud domain have been suggested. Point-BERT [32] first introduced BERT-style pre-training for point clouds, masking and reconstructing parts of the input. While achieving competitive results, their approach relies on training a separate discrete Variational AutoEncoder (dVEA) for tokenizing point cloud patches, adding complexity and dependency on tokenizer performance. Point-MAE [27] removes the tokenizer and instead reconstructs the point patches directly, using the Chamfer distance for measuring similarity between predicted and true point clouds. This speeds up training compared to Point-BERT and also improves downstream performance. MaskPoint [22] further speeds up pre-training by removing the point cloud reconstruction. Instead, the decoder is trained to discriminate between masked point patches and fake, empty ones, sampled at random.

Self-supervised learning for 3D object detection. While outdoor 3D detection has much to gain from self-supervised learning, the field is generally under-explored. STRL [19] follows the BYOL [17] approach and trains two point cloud encoders to create consistent latent representations when presented with two temporally correlated point clouds. Training two encoders can however limit model size due to increased memory requirements during pre-training. GCC-3D [21] applies contrastive learning by training models to produce voxel-wise similar features when presented with two augmented views of the same point cloud. In [13], the pre-training is done using two subsequent point clouds and the models are trained to estimate the scene flow between frames. This can be seen as a special case of masked autoencoder, where the masking is done temporally. However, their method relies on a special alternating training scheme, switching between self-supervised and supervised training. In contrast, our method enables for pre-training the models once and then fine-tuning them as needed, thus avoiding issues where large unannotated datasets have to be processed each time the model is trained toward the downstream task.

3. Methodology

This work aims to extend the MAE-style pre-training [18] to voxelized point clouds. The core idea remains to use an encoder to create rich latent representation from partial observations of the input, followed by a decoder to reconstruct the original input, as visualized in Fig. 2. After pre-training, the encoder is used as a backbone for a 3D object detector. However, due to fundamental differences between images and point clouds, several modifications are needed for the effective training of Voxel-MAE, as outlined below.

3.1. Masking and voxel embedding

Similar to the division of images into non-overlapping patches, the point cloud is first divided into voxels. Voxels bring structure to the otherwise irregular point cloud, enabling efficient processing while retaining sufficient details for dense prediction tasks such as 3D OD. However, voxels also bring unique challenges compared to image patches.

First, a large fraction of the voxels in the field of view are...
generally empty due to occlusion and the inherent sparsity of lidar data. Rather than using all voxels, we discard empty voxels to avoid unnecessary computational strain. During pre-training, we mask a large fraction (70%) of non-empty voxels and process only visible voxels with the encoder, further enhancing computational efficiency. The varying amount of visible voxels between scenes is handled elegantly by the many-to-many mapping of Transformers.

Second, due to the varying point density, the number of points assigned to individual voxels can vary from one to a few hundred. For embedding all points in each visible voxel to a single feature vector we use a dynamic voxel feature encoder [41]. Masked voxels are instead embedded with a shared, learnable mask token.

3.2. Encoder

For encoding the visible voxels we use the encoder of the Single-stride Sparse Transformer (SST) [14]. SST is a Transformer-based 3D object detector operating on voxels, making it easy to transfer pre-trained backbone weights to the downstream task of 3D OD. The SST encoder is constructed by stacking multiple Transformer encoder layers, where non-empty voxels are treated as separate tokens and point clouds are considered to be sequences of such tokens. Further, each token is accompanied by a positional embedding based on the position of the voxel in the field of view.

Since Transformers scale poorly with sequence length due to quadratic complexity in the self-attention mechanism, SST introduces regional grouping and regional shift. Inspired by the shifted windows in Swin Transformer [24], the field of view is divided into non-overlapping 3D regions. Self-attention is only calculated among voxels within the same region, drastically reducing the computational load compared to global self-attention. To enable interaction between voxels from different regions, the regions are shifted every other encoder layer and voxels are grouped according to the new regions. The combination of regional grouping and only processing non-empty voxels makes the pre-training of SST with Voxel-MAE very efficient, especially with extensive masking.

3.3. Decoder

After encoding the visible voxels, the decoder is used to leverage the rich latent representation for reconstructing the original point cloud. Note that the decoder is only used during pre-training and is discarded when fine-tuning the model toward downstream tasks. As can be seen in Fig. 2, the sequence of embedded voxels is extended with the masked voxels. These are embedded as a shared, learned mask token along with their respective positional embedding, such that the decoder can distinguish between them.

Besides the encoded and masked voxels, we also add a set of empty masked voxels, similar to what is done in [22]. We do this by sampling randomly among the empty voxels in the field of view and embedding them in the same fashion as the non-empty, masked voxels. The empty masked voxels are added to make the reconstruction task harder and effectively promote the encoder’s learning. By only processing voxels which contain points, the model would have close to perfect knowledge about occupancy, thus not having to learn about this property of point clouds. Instead, we force the decoder to learn to distinguish between non-empty and empty masked voxels and ignore empty voxels for reconstruction. Empirically, we found using 10% of the empty voxels gave the best performance, without introducing unnecessary computational overhead.

The decoder has similar structure as the encoder, again consisting of SST encoder layers, but using fewer layers. This can partially be motivated by the reduced time needed for pre-training, but we also find the encoder to achieve higher downstream task performance when trained in conjunction with a smaller decoder, similar to the results in [13].

3.4. Reconstruction target

The decoder is supervised with three different reconstruction tasks, each supervising a certain characteristic inherent to point clouds. For each task, we apply a separate linear layer to the decoder output to project the embedding to suitable dimensions. The three tasks and their corresponding loss functions are described below.

As mentioned previously, each voxel contains a varying number of points. For exact reconstruction, this would require the prediction heads to predict a different number of points for each voxel. This can be achieved using some Recurrent Neural Network for instance, but at the cost of simplicity. Instead, we propose to predict a fixed number of points for each voxel. This can be achieved using some simple linear layer for predicting said points. This reconstruction is supervised using the Chamfer distance, which measures the distance between two sets of points and allows the sets to have different cardinality. Let $P_i^\text{gt} = \{ x_j \}_{j=1}^{n_i}$ be the masked point cloud partitioned into $N$ voxels where each voxel $P^\text{pre}_i = \{ x_j \}_{j=1}^{n_i}$ contains $n_i$ points, with $n_i$ varying between voxels. Similarly, the predicted point cloud $P^\text{pre}_i = \{ \hat{x}_j \}_{j=1}^{n_i}$ for a single voxel and define our Chamfer loss as

$$
L_c = \sum_{P^\text{pre}_i \in P^\text{pre}} \frac{1}{|P^\text{pre}_i|} \sum_{x \in P^\text{pre}_i} \min_{\hat{x} \in P^\text{pre}_i} ||x - \hat{x}||_2 +
\frac{1}{|P^\text{pre}_i|} \sum_{\hat{x} \in P^\text{pre}_i} \min_{x \in P^\text{pre}_i} ||x - \hat{x}||_2.
$$

(1)

When the number of predicted points $n$ exceeds the true number of points $n_i$ in a voxel, the model can still minimize...
where the Chamfer loss by placing duplicate points in the same location. For the other scenario \( n < n_i \), it has been shown \cite{34} that the Chamfer loss encourages model predictions to capture details in the true point cloud even under cardinality mismatch.

For the model to further learn the uneven point cloud distribution explicitly we also predict the number of points \( \hat{n}_i \) for each non-empty masked voxel. As the target \( n_i \) can range from one to a few hundred, we supervise the prediction using the smooth L1 loss to avoid exploding gradients

\[
\mathcal{L}_{np} = \begin{cases} 
\frac{(n_i - \hat{n}_i)^2}{2} & \text{if } |n_i - \hat{n}_i| < 1, \\
|n_i - \hat{n}_i| - 0.5 & \text{otherwise.}
\end{cases}
\] (2)

Lastly, for each masked voxel we predict if it is empty or non-empty. This is supervised with a simple binary cross entropy loss \( \mathcal{L}_{occ} \). The total loss for the pre-training is

\[
\mathcal{L} = \alpha_c \mathcal{L}_c + \alpha_{np} \mathcal{L}_{np} + \alpha_{occ} \mathcal{L}_{occ},
\] (3)

where \( \alpha_c, \alpha_{np}, \alpha_{occ} \) are scalar weights for scaling each loss term.

4. Experiments

For our experiments, we use the popular self-driving dataset nuScenes \cite{4} which contains 1,000 sequences from Boston and Singapore, each sequence being 20 s long with raw data collected at 10 Hz, and annotations available at 2 Hz. Out of the 1,000 sequences, 850 are used for training and validation where we use established splits. All models are pre-trained on the raw training data. Following pre-training, models are fine-tuned toward the downstream task of 3D object detection.

SST \cite{14} was developed in the MMDection3D framework \cite{9} and originally evaluated in the Waymo Open Dataset \cite{31}. Due to inherent differences between the Waymo and nuScenes datasets, e.g., Waymo lidar having 64 lidar beams instead of 32, we extend the original SST implementation and tune hyperparameters for optimized nuScenes performance. For instance, we found using a slightly larger voxel size and more encoder layers yield better performance compared to the original hyperparameters. Further, following standard practice, SST was trained using aggregated point cloud sweeps. For studying sensitivity to point cloud density we evaluate our models with both 2 and 10 sweeps, where results for 2 sweeps can be found in Appendix A.3 along with additional ablations. For a complete training details see Appendix A.1

**Pre-training.** Models are trained with the AdamW optimizer \cite{49} with \( \beta_1 = 0.95, \beta_2 = 0.99 \), and weight decay of 0.01. The initial learning rate is set to 5e-5 and gradually increased over the first 1000 iterations to 5e-4 and then decayed down to 1e-7 following a cosine annealing schedule. Pre-training is run on NVIDIA A100 for 200 epochs with a batch size of four. Loss weights are set as \( \alpha_c = 1, \alpha_{np} = 0.1 \), and \( \alpha_{occ} = 1 \). The masking ratio is set to 0.7 and non-empty voxels are sampled at random. Further, the point prediction head is set to predict 10 points. When calculating the Chamfer loss, we further limit the number of true points to be fewer than 100 for computational efficiency, where points are selected at random. For remaining model details, see Appendix A.2

**Downstream task training.** When training toward the downstream task, weights for the voxel encoder and SST encoder layers are initialized either from pre-trained weights or randomly, depending on using Voxel-MAE or not. The remaining model parts are always initialized randomly. We use the AdamW optimizer with \( \beta_1 = 0.9, \beta_2 = 0.999 \), and weight decay of 0.05. The learning rate is increased from 1e-5 to 1e-3 during the first iterations and decreased with a cosine annealing schedule down to 1e-8. Models are trained for 288 epochs with a batch size of 4.

4.1. Data efficiency

**Varying amount of labeled data.** One of the major benefits of using self-supervised learning is a reduced need for annotated data. To study the effects of various dataset sizes we train SST with and without Voxel-MAE with varying fractions of the annotated dataset held out. Specifically, we use \{0.2, 0.4, 0.6, 0.8, 1.0\} of the annotated dataset for training the 3D OD models, where one model is initialized randomly and one has been pre-trained on the Voxel-MAE tasks. Pre-training was done on the entire nuScenes training dataset. To determine which scenes to use in each fraction, the training dataset was sorted based on scene timestamps. Then, scenes were chosen based on their index modulus 5, e.g., for extracting 20% of the dataset, all scenes with index \( i \) were chosen if \( i \mod 5 = 0 \), while for 40% we used \( i \mod 5 \in \{0, 2\} \) as our selection criteria. This way, the temporal dependency between frames is minimized and the reduced datasets have diversity as the entire dataset. We report mAP and NDS scores for the nuScenes validation set in Table 1.

From Table 1 we can see that by training SST from scratch with randomly initialized weights, the model achieves 49.08 mAP and 60.75 NDS when using 10 aggregated point cloud sweeps. In comparison, the pre-trained model, using only 40% of the annotated data, achieves 50.02 mAP and 61.01 NDS, hence outperforming the version without pre-training. The substantial gap of 1 mAP point indicates that even less than 40% of the annotated data would suffice.

The largest performance increase for Voxel-MAE in comparison to the baseline can be seen when fine-tuning on the smallest fraction of annotated data. In those instances, mAP is increased by close to 5 mAP points and NDS by ~3.5 points. For some individual classes, such as
Table 1: mAP, NDS, and AP per class on the nuScenes validation data for pre-trained and randomly initialized models when varying the amount of labeled data. Pre-training and fine-tuning is done with ten aggregated point cloud sweeps without intensity information. ped.=pedestrian. T.C.=traffic cone. moto.=motorcycle.

| Dataset fraction | Pre-trained | mAP  | NDS  | ped. | car | truck | bus | barrier | T.C. | trailer | moto. |
|------------------|-------------|------|------|------|-----|-------|-----|---------|------|---------|-------|
| 0.2              | ✔️          | 42.43 | 55.60| 73.5 | 78.6 | 42.5  | 49.5| 55.1    | 38.9 | 18.9    | 41.6  |
|                  | ✔️          | 47.35 | 59.06| 78.4 | 80.8 | 47.7  | 58.9| 60.5    | 46.1 | 22.2    | 45.1  |
| 0.4              | ✔️          | 47.79 | 59.11| 77.9 | 81.2 | 47.1  | 56.2| 59.0    | 46.2 | 21.6    | 47.8  |
|                  | ✔️          | 50.02 | 61.01| 81.3 | 80.3 | 49.6  | 61.1| 62.6    | 49.4 | 24.1    | 47.7  |
| 0.6              | ✔️          | 47.77 | 59.57| 78.0 | 81.2 | 46.3  | 59.1| 58.0    | 46.5 | 24.2    | 49.4  |
|                  | ✔️          | 51.00 | 61.76| 81.4 | 81.9 | 50.6  | 60.8| 63.1    | 52.9 | 25.1    | 53.1  |
| 0.8              | ✔️          | 48.26 | 59.57| 78.5 | 81.9 | 47.8  | 60.1| 59.7    | 48.7 | 23.1    | 51.6  |
|                  | ✔️          | 51.95 | 62.16| 81.4 | 82.3 | 51.2  | 63.9| 63.2    | 52.8 | 27.5    | 51.5  |

Table 2: mAP, NDS, and AP per class on the nuScenes validation data for pre-trained and randomly initialized models when varying the amount of unlabeled data. 0.0 refers to the model trained from scratch. Pre-training and fine-tuning is done with ten aggregated point cloud sweeps without intensity information. ped.=pedestrian. T.C.=traffic cone. moto.=motorcycle.

| Labeled data | Unlabeled data | mAP  | NDS  | ped. | car | truck | bus | barrier | T.C. | trailer | moto. |
|--------------|----------------|------|------|------|-----|-------|-----|---------|------|---------|-------|
| 0.0          | 8.03            | 15.4 | 45.1 | 4.6  | 1.0 | 11.3  | 2.8 | 0.0     | 0.0  | 0.0     | 0.0   |
| 0.2          | 20.05           | 55.5 | 61.5 | 14.1 | 14.2| 32.7  | 14.6| 1.0     | 6.6  | 6.6     | 6.6   |
| 0.4          | 20.75           | 58.7 | 62.4 | 14.5 | 13.8| 35.6  | 15.2| 0.8     | 6.4  | 6.4     | 6.4   |
| 0.6          | 21.07           | 60.5 | 62.4 | 14.4 | 13.4| 34.7  | 16.0| 1.3     | 7.1  | 7.1     | 7.1   |
| 0.8          | 21.23           | 60.3 | 63.9 | 15.4 | 13.1| 36.2  | 14.7| 1.0     | 7.4  | 7.4     | 7.4   |
| 1.0          | 22.18           | 62.6 | 63.8 | 16.5 | 14.4| 38.3  | 17.6| 0.9     | 6.9  | 6.9     | 6.9   |
| 0.0          | 24.99           | 56.6 | 68.5 | 22.4 | 18.2| 36.6  | 22.0| 5.5     | 16.6 | 16.6    | 16.6  |
| 0.2          | 33.93           | 71.2 | 74.1 | 33.4 | 34.6| 48.1  | 34.1| 11.9    | 21.7 | 21.7    | 21.7  |
| 0.4          | 34.88           | 72.1 | 74.7 | 33.5 | 37.1| 49.2  | 34.6| 13.2    | 23.9 | 23.9    | 23.9  |
| 0.6          | 34.74           | 72.7 | 74.5 | 34.1 | 36.5| 47.7  | 36.7| 11.1    | 22.4 | 22.4    | 22.4  |
| 0.8          | 35.07           | 72.4 | 74.6 | 35.0 | 34.7| 49.2  | 35.7| 10.6    | 25.1 | 25.1    | 25.1  |
| 1.0          | 36.01           | 73.8 | 74.9 | 34.1 | 38.2| 50.8  | 37.6| 11.2    | 23.9 | 23.9    | 23.9  |

bus, the performance boost is even larger, close to 10 AP points. Pre-training with Voxel-MAE consistently outperforms the randomly initialized equivalent, even as the entire annotated dataset is used. Naturally, the performance gap shrinks as more annotated data is used, but the gap remains large regardless of the fraction of annotated data. For instance, using all of the annotated data, Voxel-MAE results in a 2.87 mAP point and a 1.41 NDS point increase. This indicates that our pre-training is useful for learning general point cloud representations which improve both data efficiency and final performance for existing methods.

**Varying amount of unlabeled data.** We also study the effect of varying the amount of unlabeled data when keeping the amount of labeled data fixed. This simulates the scenario where the amount of unlabeled data is much greater than the amount of labeled data. For this, we pre-train five models on varying fractions of the entire dataset, namely \{0.2, 0.4, 0.6, 0.8, 1.0\}, where 1.0 is equivalent to using all available data. Next, models are fine-tuned on 1% and 5% of the annotated data. Their results, compared to a model without pre-training, are shown in Table 2.

All models pre-trained with Voxel-MAE outperform their corresponding baseline. It is notable that already using 20% of the data for pre-training brings large increases in mAP and NDS, e.g., a 12 mAP point and 16.4 NDS point increment when using 1% of the labeled data for fine-tuning. Further, performance increases as the amount of unlabeled data grow, showing that our proposed method makes effective use of large unannotated datasets. We also note that the increment in performance between some levels of unlabeled data might seem minor, compared to the step from no-pretraining to using 20% of the data. We believe this to be an effect of the nuScenes dataset and our selection method when holding out part of the data. For the 0.2 dataset, we
select frames uniformly in time, minimizing their temporal correlation. For the larger fractions, we only add frames which are already close in time to the ones contained in the 0.2 dataset, as nuScenes consists of sequence data. This limits diversity and the amount of new information being added when increasing the size of the pre-training dataset.

### 4.2. Comparison to SOTA self-supervised learning methods

While self-supervised pre-training recently has enjoyed much attention for point clouds in general, only a handful of methods have been proposed for improving automotive 3D OD performance. For nuScenes, two self-supervised techniques have been evaluated prior to this work. In [21], a voxel-based backbone is trained to create consistent latent features for two different views of the same scene using contrastive learning. In [13], the model is instead supervised to estimate the scene flow, i.e., the location of points in the consecutive frame. Further, they deploy a custom training scheme, where the training objective is altered between the self-supervised task and the object detection task.

We compare Voxel-MAE to existing methods in Table 3. Note that the models use different types of backbones, which can affect the comparison. We report mAP and NDS both for models trained from scratch and the ones pre-trained with the various self-supervised techniques. For SST, we use 10 aggregated sweeps. Further, we trained a separate version which includes intensity information for each point in both pre-training and fine-tuning, something that was omitted in the original implementation [14]. We found this to help final detection performance compared to the intensity-free version, while Voxel-MAE still shows a substantial increase compared to the baseline.

In Table 3 we see the largest increase in performance for existing methods for the PointPillars model trained by [13], with 2.04 mAP points and 1.73 NDS points. However, one should note that this is the worst-performing detector, i.e., the baseline from which it is the easiest to improve upon. By instead comparing SST to the similar performing CenterPoint models trained by [21] and [13], we see the effectiveness of our proposed Voxel-MAE approach. For the SST model with intensity information, our absolute performance gains (measured in NDS) are almost twice those for the best-performing existing methods. Looking at the SST model without intensity information, our simple Voxel-MAE brings even larger gains over existing self-supervised pre-training techniques.

### 4.3. Comparison to other Transformer backbones

The Transformer is widely used for NLP and computer vision tasks, and for automotive data, it has been used for camera-lidar fusion [1] [38] or for camera-only 3D OD [20] [23]. However, the Transformer remains relatively under-explored as a backbone feature extractor for lidar data. Pointformer [26] is the only Transformer-based lidar object detector that has been evaluated on the nuScenes dataset and we compare its performance to SST in Table 4. We can see that Pointformer outperforms SST when trained from scratch. However, by pre-training with Voxel-MAE, SST can outperform Pointformer by a substantial margin.

| Method                          | mAP   | NDS   |
|---------------------------------|-------|-------|
| PointPillars [13]               | 41.02 | 53.29 |
| [S] PointPillars [13]           | 42.06+2.04 | 55.02+1.73 |
| CenterPoint + PP [13]           | 49.13 | 59.73 |
| [S] CenterPoint + PP [13]       | 49.89+0.76 | 60.01+0.28 |
| CenterPoint + PP [21]           | 49.61 | 60.20 |
| [S] CenterPoint + PP [21]       | 50.84+1.23 | 60.76+0.56 |
| CenterPoint + V [21]            | 56.19 | 64.48 |
| [S] CenterPoint + V [21]        | 57.26+1.07 | 65.01+0.53 |
| SST                            | 49.08 | 60.75 |
| SST*                           | 51.95+2.87 | 62.16+1.41 |
| SST* + Voxel-MAE               | 53.39 | 62.95 |
| SST* + Voxel-MAE               | 55.14+1.75 | 64.00+1.05 |

Table 3: Detection performance on the nuScenes validation data for SOTA self-supervised methods. [S] indicates models have been pre-trained with a self-supervised task, while other models have been randomly initialized. PP = PointPillars. V = VoxelNet. SST* uses intensity information.

| Method                          | mAP   |
|---------------------------------|-------|
| Pointformer [26]                | 53.6  |
| SST*                            | 53.39 |
| SST* + Voxel-MAE                | 55.14 |

Table 4: Detection performance on the nuScenes validation dataset, comparing SST to existing 3D OD methods with a Transformer backbone. SST* uses intensity information.

### 4.4. Qualitative evaluation

Figure 3 shows examples of a reconstructed point cloud from the nuScenes validation set. The model displays an understanding of general shapes, predicts reasonable height for most points, and captures the characteristic lidar lines along the ground plane. We also examine generalization by visualization reconstruction results when masking ratios are different from what the model was trained with, see Fig. 4. Although more extensive masking increases noise in the reconstruction, the model produces plausible point clouds, e.g., showing awareness of the two top-left vehicles by elevating predicted points above ground level.
Figure 3: Masked (top), reconstructed (middle) and true point cloud (bottom). Left shows the entire field of view (50 × 50 meters). Right shows a zoomed in version \((x \in [0, 15], y \in [-7.5, 7.5])\) of the same scene, where the grid represents the voxels. The masking ratio is 70% of non-empty voxels. Color represents points’ height, purple being ground level and yellow is maximum height. We include reconstruction of unmasked voxels for visualization purposes, although the model has not been supervised for this.

5. Conclusions

We propose Voxel-MAE, a simple masked point modeling pre-training paradigm tailored toward voxelized point clouds. Experiments on a large-scale automotive dataset show that Voxel-MAE learns useful point cloud representations from raw lidar point clouds. Our method yields notable performance increase for a competitive Transformer-based 3D object detector. Further, our pre-training reduces the need for annotated data, enabling us to achieve competitive detection performance when using a fraction of available annotations. We hope our work can encourage further research on Transformers for automotive data.

Future directions include studies of temporal masking, similar to methods in the video domain [15, 32], to learn both spatial and temporal representations useful for multi-object tracking and motion prediction.
Broader impact. Self-supervised learning in general, and our method in particular, enable the utilization of otherwise unused data, opening up for energy-consuming training ever-larger models and potentially requiring the storage of huge datasets. Associated resources can have a negative environmental impact and also limit the development and deployment of these models to well-funded actors.

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A. Supplementary material

A.1. Baseline hyperparameters

In this section, we present hyperparameters for the 3D OD model. For training the detector, we use the same loss functions as in the original SST implementation [14], but modify hyperparameters for the nuScenes dataset. Unless stated otherwise, the same set of parameters are used for pre-training, e.g., the voxelization parameters in Table 5, the voxel encoder in Table 6 and the SST encoder in Table 7. Table 8 specifies parameters used for downstream task training only.

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| Voxel size (m)             | $0.5 \times 0.5 \times 8$                 |
| Max #point                 | $\infty$                                   |
| Max #points/voxel          | $\infty$                                   |
| Max #voxels                | $\infty$                                   |
| Point cloud range $-x$     | [-50 m, 50 m]                              |
| Point cloud range $-y$     | [-50 m, 50 m]                              |
| Point cloud range $-z$     | [-3 m, 5 m]                                |
| Voxel grid shape (x,y,z)   | (200,200,1)                                |

Table 5: Parameters used for voxelization.

| Parameter                  | Value                                      |
|----------------------------|--------------------------------------------|
| First linear layer         | 64 output channels                         |
| Second linear layer        | 128 output channels                        |

Table 6: Parameters used for voxel encoder.

A.2. Pre-training hyperparameters

In this section we present hyperparameters used for the decoder and reconstruction head using during pre-training, see Tables 9 and 10.

A.3. Results with two sweeps

A.3.1 Data efficiency

Table 12 shows the data efficiency results when pre-training and fine-tuning were done with two aggregated sweeps. Similar to the results for 10 sweeps in Table 1, we see that our Voxel-MAE brings a substantial performance increase compared to the fully supervised baseline. The baseline reaches 43.6 mAP and 55.19 NDS when using the entire training dataset. The model pre-trained with Voxel-MAE outperforms this baseline when using only 60% of the annotated data with 43.77 mAP and 55.29 NDS.

Same as for the experiments with 10 sweeps the pre-trained models consistently improve upon their baseline in terms of mAP and NDS regardless of dataset fraction. Further, the largest improvements can be found for models fine-tuned on 20% of the annotations, indicating the effectiveness of our method when the amount of unlabeled data is large compared to the annotated one. However, also when using all available annotations, pre-training can increase detection performance.
| Parameter               | Value                        |
|-------------------------|------------------------------|
| Window size             | $16 \times 16$              |
| Padding levels (train)  | [30, 60, 100, 200, 250]      |
| Padding levels (test)   | [30, 60, 100, 200, 256]      |
| #Blocks                 | 8                            |
| Input dimension         | 128                          |
| FFN hidden dimension    | 256                          |
| #Heads                  | 8                            |
| #Empty voxels           | 0.1 \cdot \#\text{voxels}    |

Table 9: Parameters for the decoder used during pre-training. The padding levels refer to the grouping of windows when passing them through a decoder block, which allows for more efficient computations.

| Parameter               | Value                        |
|-------------------------|------------------------------|
| Empty voxel loss        | BinaryCrossEntropy           |
| Number of points loss   | SmoothL1($\beta = 1$)       |
| #Predicted points (Chamfer) | 10                          |
| #Max GT points (Chamfer) | 100                          |
| $\alpha_c$              | 1                            |
| $\alpha_{np}$           | 1                            |
| $\alpha_{occ}$          | 1                            |

Table 10: Parameters for the reconstruction head used during pre-training.

| Voxel size (m) | Encoder depth | mAP | NDS |
|----------------|---------------|-----|-----|
| 0.25           | 6             | 31.43 | 50.76 |
| 0.30           | 6             | 35.93 | 52.60 |
| 0.50           | 6             | 42.79 | 55.54 |
| 0.50           | 8             | 43.60 | 55.19 |
| 0.70           | 6             | 41.73 | 54.69 |
| 0.70           | 8             | 31.31 | 54.21 |

Table 11: Performance on the nuScenes validation dataset for a model using 2 sweeps and without any pre-training.

A.3.2 Loss ablation

For the models trained on two sweeps, we also study the effect of our different reconstruction loss functions. Similar to our main results, the total reconstruction loss is found by weighing together the individual terms. We use $\alpha_c = 1$, $\alpha_{np} = 1$, and $\alpha_{occ} = 1$ for the Chamfer loss, number of points loss and empty voxel loss. All other training parameters are the same as for regular pre-training. We report mAP, NDS and AP for individual classes for the fine-tuned models in Table 13.

We start by inspecting the Chamfer loss. A simple extension of previous work on masked autoencoder [18, 27] to voxels would likely entail using only the Chamfer loss. However, we observe that pre-training using only this loss does not bring any clear advantages over our baseline. When instead combining the Chamfer loss with the number of points loss, empty/non-empty classification loss, or both, there is a notable performance increase. This highlights that effective pre-training requires the reconstruction to capture the unique properties of automotive point clouds, such as sparsity and uneven point density.

The highest performing combination is using the Chamfer loss and the binary classification, or the number of points and the classification task, depending on if NDS or mAP is used as a criterion. Interestingly, using only two out of three reconstruction tasks seems to yield better performance than combining all of them. For instance, adding the Chamfer loss to the number of points loss and classification loss reduces mAP by 0.63 and NDS by 0.11. However, when the Chamfer loss is added to the number of points loss only configuration, mAP is increased by 0.76 and NDS by 0.27. We theorize that this only is a question of hyperparameter optimization. Extensive tuning $\alpha_c$, $\alpha_{np}$, and $\alpha_{occ}$ was considered out of scope for this work, but would most likely result in even larger improvements over the baseline model.

A.3.3 Encoder depth and voxel size

In Table 11 we study how baseline performance varies with different number of encoder layers and voxel size. For reference, the original SST model was tuned toward the Waymo Open dataset and used 6 encoder layers and a voxel size of $0.25 \times 0.25 \times 6$ m. However, for nuScenes, we found better performance with 8 encoder layers and a voxel size of $0.5 \times 0.5 \times 8$ m.
| Dataset fraction | Pre-trained | mAP   | NDS   | ped. | car  | truck | bus   | barrier | T.C. | trailer | moto. |
|------------------|-------------|-------|-------|------|------|-------|-------|---------|------|---------|-------|
| 0.2              | ✗           | 35.54 | 47.79 | 62.5 | 73.6 | 35.8  | 41.7  | 49.4    | 31.2 | 14.8    | 29.5  |
|                  | ✓           | 39.95 | 51.60 | 69.1 | 75.7 | 40.4  | 48.1  | 54.6    | 39.3 | 18.2    | 33.6  |
| 0.4              | ✗           | 38.99 | 51.41 | 66.7 | 76.8 | 39.8  | 48.2  | 51.9    | 34.9 | 17.9    | 35.4  |
|                  | ✓           | 43.15 | 54.46 | 71.4 | 77.5 | 43.0  | 54.2  | 57.5    | 41.0 | 20.7    | 38.4  |
| 0.6              | ✗           | 41.29 | 53.28 | 69.1 | 77.4 | 41.3  | 50.8  | 54.9    | 37.4 | 20.0    | 38.7  |
|                  | ✓           | 43.77 | 55.29 | 72.1 | 77.8 | 44.0  | 54.5  | 57.4    | 43.8 | 21.8    | 40.7  |
| 0.8              | ✗           | 42.26 | 54.24 | 69.2 | 77.8 | 40.8  | 53.6  | 55.4    | 40.2 | 19.4    | 39.6  |
|                  | ✓           | 43.96 | 55.57 | 72.2 | 77.8 | 43.0  | 55.0  | 57.9    | 42.6 | 22.1    | 41.7  |
| 1.0              | ✗           | 43.60 | 55.19 | 69.9 | 78.9 | 43.1  | 55.7  | 56.7    | 39.5 | 21.4    | 41.5  |
|                  | ✓           | 44.62 | 56.00 | 72.1 | 78.3 | 43.0  | 54.5  | 57.3    | 43.2 | 21.2    | 44.9  |

Table 12: mAP, NDS, and AP per class on the nuScenes validation data for pre-trained and randomly initialized models when varying the amount of labeled data. Pre-training and fine-tuning is done with two aggregated point cloud sweeps without intensity information. ped.=pedestrian. T.C.=traffic cone. moto.=motorcycle.

| Chamfer | #Points | Empty | mAP   | NDS   | ped. | car  | truck | bus   | barrier | T.C. | trailer | moto. |
|---------|---------|-------|-------|-------|------|------|-------|-------|---------|------|---------|-------|
| ✓       | 43.60   | 55.19 | 69.9  | 78.9  | 43.1 | 55.7 | 56.7  | 39.5  | 21.4    | 41.5 |
| ✓       | 43.46   | 55.29 | 72.4  | 78.3  | 40.7 | 55.1 | 33.6  | 41.6  | 19.5    | 43.0 |
| ✓       | 42.27   | 55.83 | 72.8  | 78.8  | 44.4 | 55.5 | 58.3  | 42.7  | 19.8    | 43.4 |
| ✓       | 45.03   | 56.10 | 72.9  | 79.1  | 45.7 | 55.6 | 58.7  | 44.1  | 21.5    | 44.5 |
| ✓       | 44.82   | 56.25 | 72.3  | 79.4  | 44.5 | 57.1 | 57.4  | 42.3  | 21.0    | 44.9 |
| ✓       | 45.25   | 56.11 | 71.7  | 78.9  | 45.0 | 57.0 | 58.6  | 42.8  | 22.7    | 44.6 |
| ✓       | 44.62   | 56.00 | 72.1  | 78.3  | 43.0 | 54.5 | 57.3  | 43.2  | 21.2    | 44.9 |

Table 13: mAP, NDS, and AP per class on the nuScenes validation data for pre-trained models for different combinations of reconstruction tasks. Pre-training and fine-tuning is done with two aggregated point cloud sweeps without intensity information. ped.=pedestrian. T.C.=traffic cone. moto.=motorcycle.