MOT16: A Benchmark for Multi-Object Tracking

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Abstract—Standardized benchmarks are crucial for the majority of computer vision applications. Although leaderboards and ranking tables should not be over-claimed, benchmarks often provide the most objective measure of performance and are therefore important guides for reseach. Recently, a new benchmark for Multiple Object Tracking, *MOTChallenge*, was launched with the goal of collecting existing and new data and creating a framework for the standardized evaluation of multiple object tracking methods [27]. The first release of the benchmark focuses on multiple people tracking, since pedestrians are by far the most studied object in the tracking community. This paper accompanies a new release of the *MOTChallenge* benchmark. Unlike the initial release, all videos of *MOT16* have been carefully annotated following a consistent protocol. Moreover, it not only offers a significant increase in the number of labeled boxes, but also provides multiple object classes beside pedestrians and the level of visibility for every single object of interest.

Index Terms—multiple people tracking, benchmark, evaluation metrics, dataset

✦

1 INTRODUCTION

Evaluating and comparing multi-target tracking methods is not trivial for numerous reasons (*cf. e.g.* [33]). First, unlike for other tasks, such as image denoising, the ground truth, *i.e.* the perfect solution one aims to achieve, is difficult to define clearly. Partially visible, occluded, or cropped targets, reflections in mirrors or windows, and objects that very closely resemble targets all impose intrinsic ambiguities, such that even humans may not agree on one particular ideal solution. Second, a number of different evaluation metrics with free parameters and ambiguous definitions often lead to conflicting quantitative results across the literature. Finally, the lack of pre-defined test and training data makes it difficult to compare different methods fairly.

Even though multi-target tracking is a crucial problem in scene understanding, until recently it still lacked large-scale benchmarks to provide a fair comparison between tracking methods. In 2014, we released the *MOTChallenge* benchmark, which consisted of three main components: (1) a (re-)collection of publicly available and new datasets, (2) a centralized evaluation method, and (3) an infrastructure that allows for crowdsourcing of new data, new evaluation methods and even new annotations. The first release of the dataset named *MOT15* consisted of 11 sequences for training and 11 for testing, with a total of 11286 frames or 996 seconds of video. Pre-computed object detections, annotations (only for the training sequences), and a common evaluation method

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for all datasets was provided to all participants, which allowed for all results to be compared in a fair way.

Since October 2014, 47 methods have been publicly tested on the *MOTChallenge* benchmark, and over 180 users have registered. It has been established as a new standard benchmark for multiple people tracking, and methods have improved accuracy by over 10%. The first workshop [2] organized on the *MOTChallenge* benchmark took place in early 2015 in conjunction with the Winter Conference on Applications of Computer Vision (WACV). Despite its success, *MOT15* is lacking in a few aspects:

- The annotation protocol is not consistent across all sequences since some of the ground truth was collected from various sources with already available annotations;
- the distribution of crowd density is not balanced for training and test sequences;
- some of the sequences are easy and well-known (*e.g.* PETS09-S2L1) and methods are overfitted to them, which makes them not ideal for training purposes;
- the provided detections did not show good performance on the benchmark, which made some participants switch to another pedestrian detector.

In order to improve the above shortcomings, we now introduce the new *MOT16* benchmark, a set of 14 sequences with more crowded scenarios, different viewpoints, camera motions and weather conditions. Most importantly, the annotations for *all* sequences have been carried out by qualified researchers from scratch following a strict protocol, and finally double-checked to ensure highest annotation accuracy. Not only pedestrians are annotated, but also vehicles, sitting people, occluding objects, as well as other significant object classes. With this fine-grained level of annotation it is possible to accurately compute the degree of occlusion and cropping

of all bounding boxes, which is also provided with the benchmark. We hope that this rich ground truth information will be very useful to the community in order to develop even more accurate tracking methods and advancing the field further. This paper has thus three main goals:

1) To present the new *MOT16* benchmark for fair evaluation of multi-target tracking methods;
2) to detail the annotation protocol strictly followed to create the ground truth of the benchmark;
3) to bring forward the strengths and weaknesses of state-of-the-art multi-target tracking methods.

The benchmark with all datasets, current ranking and submission guidelines can be found at:

http://www.motchallenge.net/

1.1 Related work

Benchmarks and challenges. In the recent past, the computer vision community has developed centralized benchmarks for numerous tasks including object detection [14], pedestrian detection [12], 3D reconstruction [38], optical flow [7], [18], visual odometry [18], single-object short-term tracking [25], and stereo estimation [18], [36]. Despite potential pitfalls of such benchmarks (*e.g.* [41]), they have proven to be extremely helpful to advance the state of the art in the respective area. For multiple target tracking, in contrast, there has been very limited work on standardizing quantitative evaluation.

One of the few exceptions is the well known PETS dataset [16], targeted primarily at surveillance applications. The 2009 version consisted of 3 subsets: S1 targeted at person count and density estimation, S2 targeted at people tracking, and S3 targeted at flow analysis and event recognition. The easiest sequence for tracking (S2L1) consisted of a scene with few pedestrians, and for that sequence state-of-the-art methods perform extremely well with accuracies of over 90% given a good set of initial detections [22], [32], [46]. Methods then moved to tracking on the hardest sequence (*i.e.* with the highest crowd density), but hardly ever on the complete dataset. Even for this widely used benchmark, we observe that tracking results are commonly obtained in an inconsistent fashion: involving using different subsets of the available data, inconsistent model training that is often prone to overfitting, varying evaluation scripts, and different detection inputs. Results are thus not easily comparable. Hence, the question that arises is: Are these sequences already too easy for current tracking methods, are methods simply overfit, or are they poorly evaluated?

The PETS team organizes a workshop approximately once a year to which researchers can submit their results, and methods are evaluated under the same conditions. Although this is indeed a fair comparison, the fact that submissions are evaluated only once a year means that the use of this benchmark for high impact conferences

like ICCV or CVPR remains challenging. Furthermore, the sequences tend to be focused only on surveillance scenarios, and lately on specific tasks such as vessel tracking.

A well-established and useful way of organizing datasets is through standardized challenges. These are usually in the form of web servers that host the data and through which results are uploaded by the users. Results are then computed in a centralized way by the server and afterwards presented online to the public, making comparison with any other method immediately possible. There are several datasets organized in this fashion: the Labeled Faces in the Wild [23] for unconstrained face recognition, the PASCAL VOC [14] for object detection, the ImageNet large scale visual recognition challenge [35], or the Reconstruction Meets Recognition Challenge (RMRC) [1].

Recently, the KITTI benchmark [18] was introduced for challenges in autonomous driving, which included stereo/flow, odometry, road and lane estimation, object detection and orientation estimation, as well as tracking. Some of the sequences include crowded pedestrian crossings, making the dataset quite challenging, but the camera position is always the same for all sequences (at a car's height).

Another work that is worth mentioning is [4], in which the authors collected a very large amount of data with 42 million pedestrian trajectories. Since annotation of such a large collection of data is infeasible, they use a denser set of cameras to create the "ground truth" trajectories. Though we do not aim at collecting such a large amount of data, the goal of our benchmark is somewhat similar: to push research in tracking forward by generalizing the test data to a larger set that is highly variable and hard to overfit.

In the near future, DETRAC, a new benchmark for vehicle tracking [43], is going to open a similar submission system to the one we proposed with *MOTChallenge*. The benchmark consists of a total of 100 sequences, 60% of which is used for training. Sequences are filmed from a high viewpoint (surveillance scenarios) with the goal of vehicle tracking.

With the *MOT16* release within the *MOTChallenge* benchmark, we aim to increase the difficulty by including a variety of sequences filmed from different viewpoints, with different lighting conditions, and far more crowded scenarios when compared to our first release.

Evaluation. A critical point with any dataset is how to measure the performance of the algorithms. In the case of multiple object tracking, the CLEAR metrics [24] have emerged as one of the standard measures. We will discuss them in more detail in Sec. 4.1. By measuring the intersection over union of bounding boxes and matching those from ground truth annotations and results, measures of accuracy and precision can be computed. Precision measures how well the persons are localized,
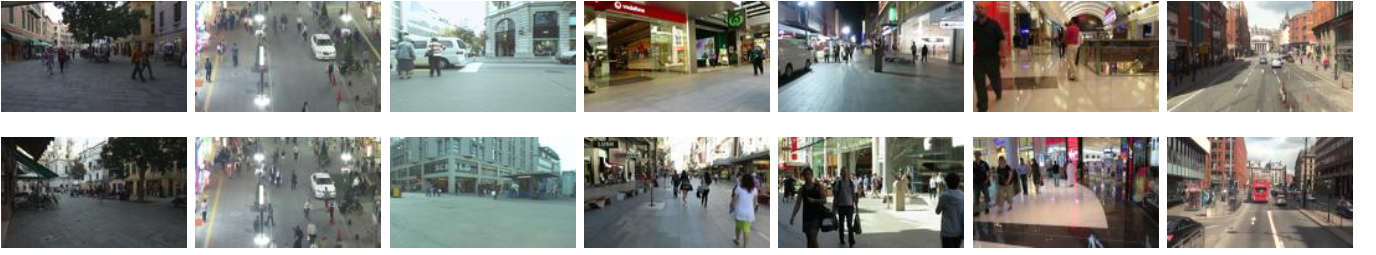
Fig. 1: An overview of the *MOT16* dataset. Top: Training sequences; bottom: test sequences.

while accuracy evaluates how many distinct errors such as missed targets, ghost trajectories, or identity switches are made.

Another set of measures that is widely used in the tracking community is that of [29]. There are three widely used metrics introduced in that work: mostly tracked, mostly lost, and partially tracked pedestrians. These numbers give a very good intuition on the performance of the method. We refer the reader to [27] for more formal definitions.

A key parameter in both families of metrics is the intersection-over-union threshold, which determines if a bounding box is matched to an annotation or not. It is fairly common to observe methods compared under different thresholds, varying from 25% to 50%. There are often many other variables and implementation details that differ between evaluation scripts, but which may affect results significantly.

It is therefore clear that standardized benchmarks are the only way to compare methods in a fair and principled way. Using the same ground truth data and evaluation methodology is the only way to guarantee that the only part being evaluated is the tracking method that delivers the results. This is the main goal behind this paper and behind the *MOTChallenge* benchmark.

2 ANNOTATION RULES

We follow a set of rules to annotate every moving person or vehicle within each sequence with a bounding box as accurately as possible. In the following we define a clear protocol that was obeyed throughout the entire dataset to guarantee consistency.

2.1 Target class

In this benchmark we are interested in tracking moving objects in videos. In particular, we are interested in evaluating multiple people tracking algorithms, therefore, people will be the center of attention of our annotations. We divide the pertinent classes into three categories:
(i) *moving* or *standing* pedestrians;
(ii) people that are *not in an upright position* or artificial representations of humans; and
(iii) *vehicles* and *occluders*.

In the first group, we annotate all moving or standing (upright) pedestrians that appear in the field of view and can be determined as such by the viewer. People

on bikes or skateboards will also be annotated in this category (and are typically found by modern pedestrian detectors). Furthermore, if a person *briefly* bends over or squats, *e.g.* to pick something up or to talk to a child, they shall remain in the standard *pedestrian* class. The algorithms that submit to our benchmark are expected to track these targets.

In the second group we include all people-like objects whose exact classification is ambiguous and can vary depending on the viewer, the application at hand, or other factors. We annotate all static people that are not in an upright position, *e.g.* sitting, lying down. We also include in this category any artificial representation of a human that might fire a detection response, such as mannequins, pictures, or reflections. People behind glass should also be marked as distractors. The idea is to use these annotations in the evaluation such that an algorithm is neither penalized nor rewarded for tracking, *e.g.*, a sitting person or a reflection.

In the third group, we annotate all moving vehicles such as cars, bicycles, motorbikes and non-motorized vehicles (*e.g.* strollers), as well as other potential occluders. These annotations will not play any role in the evaluation, but are provided to the users both for training purposes and for computing the level of occlusion of pedestrians. Static vehicles (parked cars, bicycles) are not annotated as long as they do not occlude any pedestrians.

The rules are summarized in Tab. 1 and in Fig. 2 we present a diagram of the classes of objects we annotate, as well as a sample frame with annotations.

2.2 Bounding box alignment

The bounding box is aligned with the object's extent as accurately as possible. The bounding box should contain all pixels belonging to that object and at the same time be as tight as possible, *i.e.* no pixels should be left outside the box. This means that a walking side-view pedestrian will typically have a box whose width varies periodically with the stride, while a front view or a standing person will maintain a more constant aspect ratio over time. If the person is partially occluded, the extent is estimated based on other available information such as expected size, shadows, reflections, previous and future frames and other cues. If a person is cropped by the image border, the box is estimated beyond the original frame
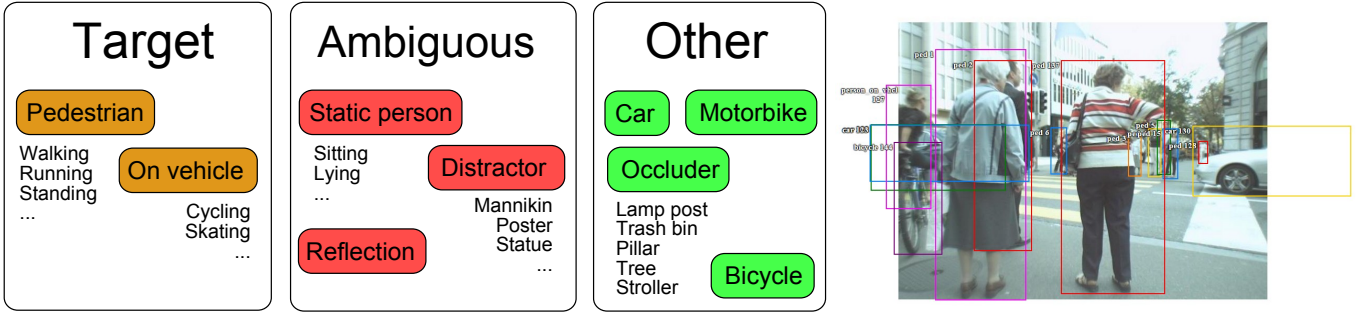
Fig. 2: Left: An overview of annotated classes. The classes in orange will be the central ones to evaluate on. The red classes include ambiguous cases such that both recovering and missing them will not be penalized in the evaluation. The classes in green are annotated for training purposes and for computing the occlusion level of all pedestrians. Right: An exemplar of an annotated frame. Note how partially cropped objects are also marked outside of the frame. Also note that the bounding box encloses the entire person but not *e.g.* the white bag of Pedestrian 1 (bottom left).

	Instruction
What?	Targets: All upright people including + walking, standing, running pedestrians + cyclists, skaters Distractors: Static people or representations + people not in upright position (sitting, lying down) + reflections, drawings or photographs of people + human-like objects like dolls, mannequins Others: Moving vehicles and occluders + Cars, bikes, motorbikes + Pillars, trees, buildings
When?	Start as early as possible. End as late as possible. Keep ID as long as the person is inside the field of view and its path can be determined unambiguously.
How?	The bounding box should contain all pixels belonging to that person and at the same time be as tight as possible.
Occlusions	Always annotate during occlusions if the position can be determined unambiguously. If the occlusion is very long and it is not possible to determine the path of the object using simple reasoning (*e.g.* constant velocity assumption), the object will be assigned a new ID once it reappears.

TABLE 1: Instructions obeyed during annotations.

to represent the entire person and to estimate the level of cropping. If an occluding object cannot be accurately enclosed in one box (*e.g.* a tree with branches or an escalator may require a large bounding box where most of the area does not belong to the actual object), then several boxes may be used to better approximate the extent of that object.

Persons on vehicles will only be annotated separately from the vehicle if clearly visible. For example, children inside strollers or people inside cars will not be annotated, while motorcyclists or bikers will be.

2.3 Start and end of trajectories

The box (track) appears as soon as the person's location and extent can be determined precisely. This is typically the case when $\approx 10\%$ of the person becomes visible. Similarly, the track ends when it is no longer possible

to pinpoint the exact location. In other words the annotation starts as early and ends as late as possible such that the accuracy is not forfeited. The box coordinates may exceed the visible area. Should a person leave the field of view and appear at a later point, they will be assigned a new ID.

2.4 Minimal size

Although the evaluation will only take into account pedestrians that have a minimum height in pixels, annotations will contain all objects of all sizes as long as they are distinguishable by the annotator. In other words, *all* targets independent of their size on the image shall be annotated.

2.5 Occlusions

There is no need to explicitly annotate the level of occlusion. This value will be computed automatically using the ground plane assumption and the annotations. Each target is fully annotated through occlusions as long as its extent and location can be determined accurately enough. If a target becomes completely occluded in the middle of the sequence and does not become visible later, the track should be terminated (marked as 'outside of view'). If a target reappears after a prolonged period such that its location is ambiguous during the occlusion, it will reappear with a new ID.

3 DATASETS

One of the key aspects of any benchmark is data collection. The goal of *MOT16* is to compile a benchmark with new sequences, which are more challenging than the ones presented in *MOT15*. In Fig. 1 and Tab. 2 we show an overview of the sequences included in the benchmark.

Training sequences										
Name	FPS	Resolution	Length	Tracks	Boxes	Density	Camera	Viewpoint	Conditions	Source
MOT16-02	30	1920x1080	600 (00:20)	49	17812	29.7	static	medium	cloudy	new
MOT16-04	30	1920x1080	1050 (00:35)	80	47551	45.3	static	high	night	new
MOT16-05	14	640x480	837 (01:00)	124	6818	8.1	moving	medium	sunny	[13]
MOT16-09	30	1920x1080	525 (00:18)	25	5257	10.0	static	low	indoor	new
MOT16-10	30	1920x1080	654 (00:22)	54	12318	18.8	moving	medium	night	new
MOT16-11	30	1920x1080	900 (00:30)	67	9168	10.2	moving	medium	indoor	new
MOT16-13	25	1920x1080	750 (00:30)	68	11419	15.2	moving	high	sunny	new
Total training			**5316 (03:35)**	**467**	**110343**	**20.8**				

Testing sequences										
Name	FPS	Resolution	Length	Tracks	Boxes	Density	Camera	Viewpoint	Conditions	Source
MOT16-01	30	1920x1080	450 (00:15)	23	6395	14.2	static	medium	cloudy	new
MOT16-03	30	1920x1080	1500 (00:50)	148	104529	69.7	static	high	night	new
MOT16-06	14	640x480	1194 (01:25)	209	11538	9.7	moving	medium	sunny	[13]
MOT16-07	30	1920x1080	500 (00:17)	53	16322	32.6	moving	medium	shadow	new
MOT16-08	30	1920x1080	625 (00:21)	63	16727	26.8	static	medium	sunny	new
MOT16-12	30	1920x1080	900 (00:30)	86	8291	9.2	moving	medium	indoor	new
MOT16-14	25	1920x1080	750 (00:30)	160	18488	24.7	moving	high	sunny	new
Total testing			**5919 (04:08)**	**742**	**182290**	**30.8**				

TABLE 2: Overview of the sequences currently included in the *MOT16* benchmark.

Annotation classes													
Sequence	Pedes-trian	Person on vehicle	Car	Bicy-cle	Mo-tor-bike	Non motor-ized vehicle	Static per-son	Dis-trac-tor	Oc-cluder	Oc-cluder on the ground	Oc-cluder full	Re-flec-tion	Total
MOT16-01	6395	346	0	341	0	0	4790	900	3150	0	0	0	15922
MOT16-02	17833	1549	0	1559	0	0	5271	1200	1781	0	0	0	29193
MOT16-03	104556	70	1500	12060	1500	0	6000	0	0	24000	13500	0	163186
MOT16-04	47557	0	1050	11550	1050	0	4798	0	0	23100	18900	0	108005
MOT16-05	6818	315	196	315	0	11	0	16	0	0	0	0	7671
MOT16-06	11538	150	0	118	0	0	269	238	109	0	0	0	12422
MOT16-07	16322	0	0	0	0	0	2023	0	0	1920	0	0	20265
MOT16-08	16737	0	0	0	0	0	1715	2719	6875	0	0	0	28046
MOT16-09	5257	0	0	0	0	0	0	1575	1050	0	0	948	8830
MOT16-10	12318	0	25	0	0	0	1376	470	0	2740	0	0	16929
MOT16-11	9174	0	0	0	0	0	0	306	596	0	0	0	10076
MOT16-12	8295	0	0	0	0	0	1012	765	1394	0	0	0	11464
MOT16-13	11450	0	4484	103	0	0	0	4	0	2542	680	0	19263
MOT16-14	18483	0	1563	0	0	0	712	47	0	4062	393	0	25260
Total	292733	2430	8818	26046	2550	11	27966	8238	14955	58364	33473	948	476532

TABLE 3: Overview of the types of annotations currently found in the *MOT16* benchmark.

3.1 2D MOT 2016 sequences

We have compiled a total of 14 sequences, of which we use half for training and half for testing. The annotations of the testing sequences will not be released in order to avoid (over)fitting of the methods to the specific sequences.

Sequences are very different from each other, we can classify them according to:

- Moving or static camera – the camera can be held by a person, placed on a stroller or on a car, or can be positioned fixed in the scene.
- Viewpoint – the camera can overlook the scene from a high position, a medium position (at pedestrian's height), or at a low position.
- Conditions – the weather conditions in which the sequence was taken are reported in order to obtain an estimate of the illumination conditions of the scene. Sunny sequences may contain shadows and saturated parts of the image, while the night sequence contains a lot of motion blur, making pedestrian detection and tracking rather challenging. Cloudy sequences on the other hand contain fewer of those artifacts.

The new data contains almost 3 times more bounding boxes for training and testing compared to *MOT15*. Most sequences are filmed in high resolution, and the mean crowd density is 3 times higher when compared to the first benchmark release. Hence, we expect the new sequences to be more challenging for the tracking community. In Tab. 2, we give an overview of the training and testing sequence characteristics for the challenge, including the number of bounding boxes used.

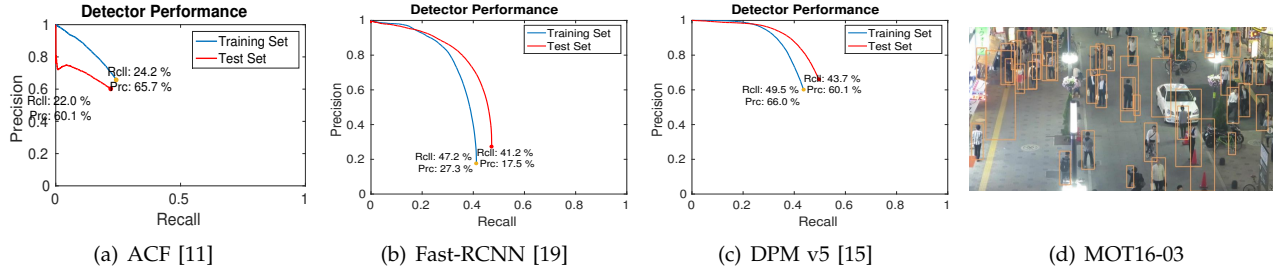(a) ACF [11]   (b) Fast-RCNN [19]   (c) DPM v5 [15]   (d) MOT16-03

Fig. 3: (a) The performance of three popular pedestrian detectors evaluated on the training (blue) and the test (red) set. The circle indicates the operating point (*i.e.* the input detection set) for the trackers. (d) Exemplar detection results. As can be seen, DPM provides the highest recall at the best precision, which is why we release only this detection set to the public.

Aside from pedestrians, the annotations also include other classes like vehicles, bicycles, etc. as detailed in Sec. 2. In Tab. 3, we detail the types of annotations that can be found in each sequence of *MOT16*.

3.2 Detections

We tested several state-of-the-art detectors on our benchmark, obtaining the Precision-Recall curves in Fig. 3. Note that the deformable part-based model (DPM) v5 [15], [21] outperforms the other detectors in the task of pedestrian detection. As noted in [20], out-of-the-box R-CNN outperforms DPM in detecting all object classes except for the class "person", which is why we supply DPM detections with the benchmark. We use the pretrained model with a low threshold of -1 in order to maintain relatively high recall. Note that the recall does not reach 100% because of the non-maximum suppression applied. Exemplar detection results are shown in Fig. 3.

A detailed breakdown of detection bounding boxes on individual sequences is provided in Tab. 4.

Seq	nDet.	nDet./fr.	min height	max height
MOT16-01	3775	8.39	19.00	258.92
MOT16-02	7267	12.11	19.00	341.97
MOT16-03	85854	57.24	19.00	297.57
MOT16-04	39437	37.56	19.00	341.97
MOT16-05	4333	5.18	19.00	225.27
MOT16-06	7851	6.58	19.00	210.12
MOT16-07	11309	22.62	19.00	319.00
MOT16-08	10042	16.07	19.00	518.84
MOT16-09	5976	11.38	19.00	451.55
MOT16-10	8832	13.50	19.00	366.58
MOT16-11	8590	9.54	19.00	518.84
MOT16-12	7764	8.63	19.00	556.15
MOT16-13	5355	7.14	19.00	210.12
MOT16-14	8781	11.71	19.00	258.92
total	215166	19.15	19.00	556.15

TABLE 4: Detection bounding box statistics.

Obviously, we cannot (nor necessarily want to) prevent anyone from using a different set of detections, or relying on a different set of features. However, we require that this is noted as part of the tracker's description and is also displayed in the ratings table for transparency.

3.3 Data format

All images were converted to JPEG and named sequentially to a 6-digit file name (*e.g.* 000001.jpg). Detection and annotation files are simple comma-separated value (CSV) files. Each line represents one object instance and contains 9 values as shown in Tab. 5.

The first number indicates in which frame the object appears, while the second number identifies that object as belonging to a trajectory by assigning a unique ID (set to -1 in a detection file, as no ID is assigned yet). Each object can be assigned to only one trajectory. The next four numbers indicate the position of the bounding box of the pedestrian in 2D image coordinates. The position is indicated by the top-left corner as well as width and height of the bounding box. This is followed by a single number, which in case of detections denotes their confidence score. The last two numbers for detection files are ignored (set to -1).

Label	ID
Pedestrian	1
Person on vehicle	2
Car	3
Bicycle	4
Motorbike	5
Non motorized vehicle	6
Static person	7
Distractor	8
Occluder	9
Occluder on the ground	10
Occluder full	11
Reflection	12

TABLE 6: Label classes present in the annotation files and ID appearing in the 7th column of the files as described in Tab. 5.

An example of such a 2D detection file is:

```
1, -1, 794.2, 47.5, 71.2, 174.8, 67.5, -1, -1
1, -1, 164.1, 19.6, 66.5, 163.2, 29.4, -1, -1
1, -1, 875.4, 39.9, 25.3, 145.0, 19.6, -1, -1
2, -1, 781.7, 25.1, 69.2, 170.2, 58.1, -1, -1
```

For the ground truth and results files, the 7th value (confidence score) acts as a flag whether the entry is to be considered. A value of 0 means that this particular

Position	Name	Description
1	Frame number	Indicate at which frame the object is present
2	Identity number	Each pedestrian trajectory is identified by a unique ID (-1 for detections)
3	Bounding box left	Coordinate of the top-left corner of the pedestrian bounding box
4	Bounding box top	Coordinate of the top-left corner of the pedestrian bounding box
5	Bounding box width	Width in pixels of the pedestrian bounding box
6	Bounding box height	Height in pixels of the pedestrian bounding box
7	Confidence score	DET: Indicates how confident the detector is that this instance is a pedestrian. GT: It acts as a flag whether the entry is to be considered (1) or ignored (0).
8	Class	GT: Indicates the type of object annotated
9	Visibility	GT: Visibility ratio, a number between 0 and 1 that says how much of that object is visible. Can be due to occlusion and due to image border cropping.

TABLE 5: Data format for the input and output files, both for detection (DET) and annotation/ground truth (GT) files.

instance is ignored in the evaluation, while a value of 1 is used to mark it as active. The 8th number indicates the type of object annotated, following the convention of Tab. 6. The last number shows the visibility ratio of each bounding box. This can be due to occlusion by another static or moving object, or due to image border cropping.

An example of such an annotation 2D file is:

```
1, 1, 794.2, 47.5, 71.2, 174.8, 1, 1, 0.8
1, 2, 164.1, 19.6, 66.5, 163.2, 1, 1, 0.5
2, 4, 781.7, 25.1, 69.2, 170.2, 0, 12, 1.
```

In this case, there are 2 pedestrians in the first frame of the sequence, with identity tags 1, 2. In the second frame, we can see a reflection (class 12), which is to be considered by the evaluation script and will neither count as a false negative, nor as a true positive, independent of whether it is correctly recovered or not. Note that all values including the bounding box are 1-based, *i.e.* the top left corner corresponds to $(1, 1)$.

To obtain a valid result for the entire benchmark, a separate CSV file following the format described above must be created for each sequence and called ``Sequence-Name.txt''. All files must be compressed into a single ZIP file that can then be uploaded to be evaluated.

4 EVALUATION

Our framework is a platform for fair comparison of state-of-the-art tracking methods. By providing authors with standardized ground truth data, evaluation metrics and scripts, as well as a set of precomputed detections, all methods are compared under the exact same conditions, thereby isolating the performance of the tracker from everything else. In the following paragraphs, we detail the set of evaluation metrics that we provide in our benchmark.

4.1 Evaluation metrics

In the past, a large number of metrics for quantitative evaluation of multiple target tracking have been proposed [8], [29], [37], [39], [40], [45]. Choosing "the right" one is largely application dependent and the quest for a unique, general evaluation metric is still ongoing. On the one hand, it is desirable to summarize the performance into one single number to enable a direct comparison. On the other hand, one might not want to lose information about the individual errors made by the algorithms and provide several performance estimates, which precludes a clear ranking.

Following a recent trend [6], [32], [44], we employ two sets of measures that have established themselves in the literature: The *CLEAR* metrics proposed by Stiefelhagen *et al.* [40], and a set of track quality measures introduced by Wu and Nevatia [45]. The evaluation scripts used in our benchmark are publicly available.[1]

4.1.1 Tracker-to-target assignment

There are two common prerequisites for quantifying the performance of a tracker. One is to determine for each hypothesized output, whether it is a true positive (TP) that describes an actual (annotated) target, or whether the output is a false alarm (or false positive, FP). This decision is typically made by thresholding based on a defined distance (or dissimilarity) measure d (see Sec. 4.1.2). A target that is missed by any hypothesis is a false negative (FN). A good result is expected to have as few FPs and FNs as possible. Next to the absolute numbers, we also show the false positive ratio measured by the number of false alarms per frame (FAF), sometimes also referred to as false positives per image (FPPI) in the object detection literature.

Obviously, it may happen that the same target is covered by multiple outputs. The second prerequisite before computing the numbers is then to establish the correspondence between all annotated and hypothesized objects under the constraint that a true object should be recovered at most once, and that one hypothesis cannot account for more than one target.

For the following, we assume that each ground truth trajectory has one unique start and one unique end point, *i.e.* that it is not fragmented. Note that the current evaluation procedure does not explicitly handle target re-identification. In other words, when a target leaves the field-of-view and then reappears, it is treated as an unseen target with a new ID. As proposed in [40], the optimal matching is found using Munkre's (a.k.a. Hungarian) algorithm. However, dealing with video data,
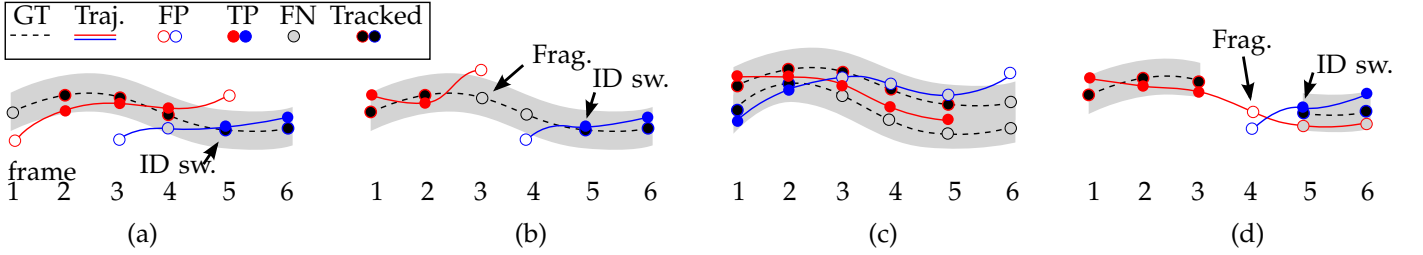
1. http://motchallenge.net/devkit

Fig. 4: Four cases illustrating tracker-to-target assignments. (a) An ID switch occurs when the mapping switches from the previously assigned red track to the blue one. (b) A track fragmentation is counted in frame 3 because the target is tracked in frames 1-2, then interrupts, and then reacquires its 'tracked' status at a later point. A new (blue) track hypothesis also causes an ID switch at this point. (c) Although the tracking results is reasonably good, an optimal single-frame assignment in frame 1 is propagated through the sequence, causing 5 missed targets (FN) and 4 false positives (FP). Note that no fragmentations are counted in frames 3 and 6 because tracking of those targets is not resumed at a later point. (d) A degenerate case illustrating that target re-identification is not handled correctly. An interrupted ground truth trajectory will typically cause a fragmentation. Also note the less intuitive ID switch, which is counted because blue is the closest target in frame 5 that is not in conflict with the mapping in frame 4.

this matching is not performed independently for each frame, but rather considering a temporal correspondence. More precisely, if a ground truth object i is matched to hypothesis j at time $t-1$ *and* the distance (or dissimilarity) between i and j in frame t is below t_d, then the correspondence between i and j is carried over to frame t even if there exists another hypothesis that is closer to the actual target. A mismatch error (or equivalently an identity switch, IDSW) is counted if a ground truth target i is matched to track j and the last known assignment was $k \neq j$. Note that this definition of ID switches is more similar to [29] and stricter than the original one [40]. Also note that, while it is certainly desirable to keep the number of ID switches low, their absolute number alone is not always expressive to assess the overall performance, but should rather be considered in relation to the number of recovered targets. The intuition is that a method that finds twice as many trajectories will almost certainly produce more identity switches. For that reason, we also state the relative number of ID switches, which is computed as IDSW / Recall.

These relationships are illustrated in Fig. 4. For simplicity, we plot ground truth trajectories with dashed curves, and the tracker output with solid ones, where the color represents a unique target ID. The grey areas indicate the matching threshold (see next section). Each true target that has been successfully recovered in one particular frame is represented with a filled black dot with a stroke color corresponding to its matched hypothesis. False positives and false negatives are plotted as empty circles. See figure caption for more details.

After determining true matches and establishing correspondences it is now possible to compute the metrics. We do so by concatenating all test sequences and evaluating on the entire benchmark. This is in general more meaningful instead of averaging per-sequences figures due to the large variation in the number of targets.

4.1.2 Distance measure

In the most general case, the relationship between ground truth objects and a tracker output is established using bounding boxes on the image plane. Similar to object detection [14], the intersection over union (a.k.a. the Jaccard index) is usually employed as the similarity criterion, while the threshold t_d is set to 0.5 or 50%.

4.1.3 Target-like annotations

People are a common object class present in many scenes, but should we track all people in our benchmark? For example, should we track static people sitting on a bench? Or people on bicycles? How about people behind a glass? We define the target class of *MOT16* as all upright people, standing or walking, that are reachable along the viewing ray without a physical obstacle, *i.e.* reflections, people behind a transparent wall or window are excluded. We also exclude from our target class people on bycicles or other vehicles. For all these cases where the class is very similar to our target class (see Figure 5), we adopt a similar strategy as in [31]. That is, a method is neither penalized nor rewarded for tracking or not tracking those similar classes. Since a detector is likely to fire in those cases, we do not want to penalize a tracker with a set of false positives for properly following that set of detections, *i.e.* of a person on a bicycle. Likewise, we do not want to penalize with false negatives a tracker that is based on motion cues and therefore does not track a sitting person.

In order to handle these special cases, we adapt the tracker-to-target assignment algorithm to perform the following steps:

1) At each frame, all bounding boxes of the result file are matched to the ground truth via the Hungarian algorithm.
2) All result boxes that overlap $> 50\%$ with one of these classes (distractor, static person, reflection, person on vehicle) are removed from the solution.
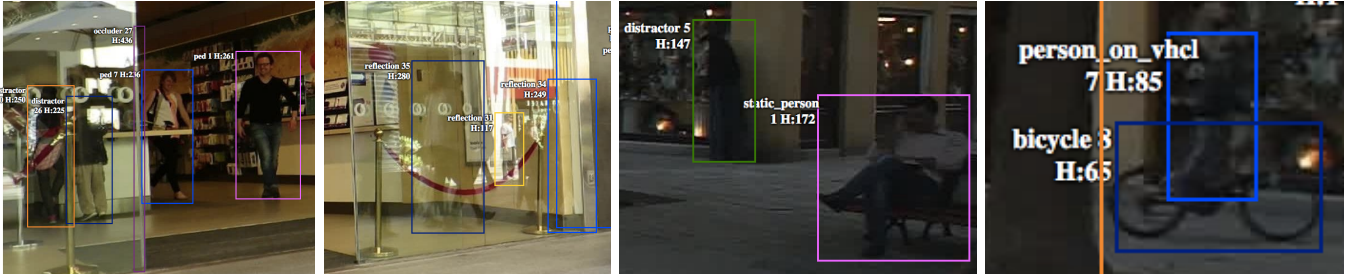
Fig. 5: The annotations include different classes of objects similar to the target class, a pedestrian in our case. We consider these special classes (distractor, reflection, static person and person on vehicle) to be so similar to the target class that a tracker should neither be penalized nor rewarded for tracking them in the sequence.

3) During the final evaluation, *only* those boxes that are annotated as *pedestrians* are used.

4.1.4 Multiple Object Tracking Accuracy

The MOTA [40] is perhaps the most widely used metric to evaluate a tracker's performance. The main reason for this is its expressiveness as it combines three sources of errors defined above:

$$\text{MOTA} = 1 - \frac{\sum_t \left(\text{FN}_t + \text{FP}_t + \text{IDSW}_t \right)}{\sum_t \text{GT}_t}, \qquad (1)$$

where t is the frame index and GT is the number of ground truth objects. We report the percentage MOTA $(-\infty, 100]$ in our benchmark. Note that MOTA can also be negative in cases where the number of errors made by the tracker exceeds the number of all objects in the scene.

Even though the MOTA score gives a good indication of the overall performance, it is highly debatable whether this number alone can serve as a single performance measure.

Robustness. One incentive behind compiling this benchmark was to reduce dataset bias by keeping the data as diverse as possible. The main motivation is to challenge state-of-the-art approaches and analyze their performance in unconstrained environments and on unseen data. Our experience shows that most methods can be heavily overfitted on one particular dataset, and may not be general enough to handle an entirely different setting without a major change in parameters or even in the model.

To indicate the robustness of each tracker across *all* benchmark sequences, we show the standard deviation of their MOTA score.

4.1.5 Multiple Object Tracking Precision

The Multiple Object Tracking Precision is the average dissimilarity between all true positives and their corresponding ground truth targets. For bounding box overlap, this is computed as

$$\text{MOTP} = \frac{\sum_{t,i} d_{t,i}}{\sum_t c_t}, \qquad (2)$$

where c_t denotes the number of matches in frame t and $d_{t,i}$ is the bounding box overlap of target i with its assigned ground truth object. MOTP thereby gives the average overlap between all correctly matched hypotheses and their respective objects and ranges between $t_d := 50\%$ and 100%.

It is important to point out that MOTP is a measure of localization precision, *not* to be confused with the *positive predictive value* or *relevance* in the context of precision / recall curves used, *e.g.*, in object detection. In practice, it mostly quantifies the localization accuracy of the detector, and therefore, it provides little information about the actual performance of the tracker.

4.1.6 Track quality measures

Each ground truth trajectory can be classified as mostly tracked (MT), partially tracked (PT), and mostly lost (ML). This is done based on how much of the trajectory is recovered by the tracking algorithm. A target is mostly tracked if it is successfully tracked for at least 80% of its life span. Note that it is irrelevant for this measure whether the ID remains the same throughout the track. If a track is only recovered for less than 20% of its total length, it is said to be mostly lost (ML). All other tracks are partially tracked. A higher number of MT and few ML is desirable. We report MT and ML as a ratio of mostly tracked and mostly lost targets to the total number of ground truth trajectories.

In certain situations one might be interested in obtaining long, persistent tracks without gaps of untracked periods. To that end, the number of track fragmentations (FM) counts how many times a ground truth trajectory is interrupted (untracked). In other words, a fragmentation is counted each time a trajectory changes its status from tracked to untracked and tracking of that same trajectory is resumed at a later point. Similarly to the ID switch ratio (*cf*. Sec. 4.1.1), we also provide the relative number of fragmentations as FM / Recall.

4.1.7 Tracker ranking

As we have seen in this section, there are a number of reasonable performance measures to assess the quality of a tracking system, which makes it rather difficult to

reduce the evaluation to one single number. To nevertheless give an intuition on how each tracker performs compared to its competitors, we compute and show the average rank for each one by ranking all trackers according to each metric and then averaging across all performance measures.

5 BASELINE METHODS

As a starting point for the benchmark, we are working on including a number of recent multi-target tracking approaches as baselines, which we will briefly outline for completeness but refer the reader to the respective publication for more details. Note that we have used the publicly available code and trained all of them in the same way[2] (*cf*. Sec. 5.1). However, we explicitly state that the provided numbers may not represent the best possible performance for each method, as could be achieved by the authors themselves. Table 7 lists current benchmark results for all baselines as well as for all anonymous entries at the time of writing of this manuscript.

5.1 Training and testing

Most of the available tracking approaches do not include a learning (or training) algorithm to determine the set of model parameters for a particular dataset. Therefore, we follow a simplistic search scheme for all baseline methods to find a good setting for our benchmark. To that end, we take the default parameter set $\Theta := \{\theta_1, \ldots, \theta_P\}$ as suggested by the authors, where P is the number of free parameters for each method. We then perform 100 independent runs on the training set with varying parameters. In each run, a parameter value θ_i is uniformly sampled around its default value in the range $[\frac{1}{2}\theta_i, 2\theta_i]$. Finally, the parameter set Θ^* that achieved the highest MOTA score across all 100 runs (*cf*. Sec. 4.1.4) is taken as the optimal setting and run once on the test set. The optimal parameter set is stated in the description entry for each baseline method on the benchmark website.

5.2 DP_NMS: Network flow tracking

Since its original publication [48], a large number of methods that are based on the network flow formulation have appeared in the literature [9], [28], [30], [34], [42]. The basic idea is to model the tracking as a graph, where each node represents a detection and each edge represents a transition between two detections. Special source and sink nodes allow spawning and absorbing trajectories. A solution is obtained by finding the minimum cost flow in the graph. Multiple assignments and track splitting is prevented by introducing binary and linear constraints.

Here we use two solvers: (i) the successive shortest paths approach [34] that employs dynamic programming

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2. Except for TBD, which does not disclose any obvious free parameters.

with non-maxima suppression, termed DP_NMS; (ii) a linear programming solver that appears as a baseline in [26]. This solver uses the Gurobi Library [3].

5.3 CEM: Continuous energy minimization

CEM [32] formulates the problem in terms of a high-dimensional continuous energy. Here, we use the basic approach [5] without explicit occlusion reasoning or appearance model. The target state $\mathbf{X}$ is represented by continuous x, y coordinates in *all* frames. The energy $E(\mathbf{X})$ is made up of several components, including a data term to keep the solution close to the observed data (detections), a dynamic model to smooth the trajectories, an exclusion term to avoid collisions, a persistence term to reduce track fragmentations, and a regularizer. The resulting energy is highly non-convex and is minimized in an alternating fashion using conjugate gradient descent and deterministic jump moves.

5.4 SMOT: Similar moving objects

The Similar Multi-Object Tracking (SMOT) approach [10] specifically targets situations where target appearance is ambiguous and rather concentrates on using the motion as a primary cue for data association. Tracklets with similar motion are linked to longer trajectories using the generalized linear assignment (GLA) formulation. The motion similarity and the underlying dynamics of a tracklet are modeled as the order of a linear regressor approximating that tracklet.

5.5 TBD: Tracking-by-detection

This two-stage tracking-by-detection (TBD) approach [17], [47] is part of a larger traffic scene understanding framework and employs a rather simple data association technique. The first stage links overlapping detections with similar appearance in successive frames into tracklets. The second stage aims to bridge occlusions of up to 20 frames. Both stages employ the Hungarian algorithm to optimally solve the matching problem. Note that we did not re-train this baseline but rather used the original implementation and parameters provided.

5.6 TC_ODAL: Tracklet confidence

Robust Online Multi-Object Tracking based on Tracklet Confidence and Online Discriminative Appearance Learning, or TC_ODAL [6], is the only online method among the baselines. It proceeds in two stages. First, close detections are linked to form a set of short, reliable tracklets. This so-called local association allows one to progressively aggregate confident tracklets. In case of occlusions or missed detections, the tracklet confidence value is decreased and a global association is employed to bridge longer occlusion gaps. Both association techniques are formulated as bipartite matching and tackled with the Hungarian algorithm.

Method	AvgRank	MOTA	MOTP	FAR	MT(%)	ML(%)	FP	FN	IDsw	rel.ID	FM	rel.FM	Hz	Ref.
SMOT	x	29.2 $_{\pm 7.9}$	75.2	3.0	4.9	53.3	17929	108041	3072	75.4	4437	108.9	0.2	[10]
DP_NMS	x	32.2 $_{\pm 9.7}$	76.4	0.2	5.4	61.6	1124	121545	976	29.3	948	28.5	212.6	[34]

TABLE 7: Quantitative results of the baselines on MOT16.

Another prominent component of TC_ODAL is online appearance learning. To that end, positive samples are collected from tracklets with high confidence and incremental linear discriminant analysis (ILDA) is employed to update the appearance model in an online fashion.

6 CONCLUSION AND FUTURE WORK

We have presented a new challenging set of sequences within the *MOTChallenge* benchmark. The 2016 sequences contain 3 times more targets to be tracked when compared to the initial 2015 version. Furthermore, more accurate annotations were carried out following a strict protocol, and extra classes such as vehicles, sitting people, reflections or distractors were also annotated to provide further information to the community. We believe that the *MOT16* release within the already established *MOTChallenge* benchmark provides a fairer comparison of state-of-the-art tracking methods, and challenges researchers to develop more generic methods that perform well in unconstrained environments and on unseen data. In the future, we plan to continue our workshops and challenges series, and also introduce various other (sub-)benchmarks for targeted applications, *e.g.* sport analysis, or biomedical cell tracking.

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