Supplementary material:

Depth-attentional Features for Single-image Rain Removal

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There are four parts in this supplementary material.

Part 1 presents additional comparison results against the following rain removal methods and rain + haze removal methods:

- Rain Removal Methods:
  - ***DID-MDN:*** H. Zhang and V. M. Patel. Density-aware single image deraining using a multi-stream dense network. In *CVPR*, pages 695–704, 2018.
  - ***RESCAN:*** X. Li, J. Wu, Z. Lin, H. Liu, and H. Zha. Recurrent squeeze-and-excitation context aggregation net for single image deraining. In *ECCV*, pages 262–277, 2018.
  - ***JBO:*** L. Zhu, C.-W. Fu, D. Lischinski, and P.-A. Heng. Joint bilayer optimization for single-image rain streak removal. In *ICCV*, pages 2526–2534, 2017.
  - ***GMMLP:*** Y. Li, R. T. Tan, X. Guo, J. Lu, and M. S. Brown. Rain streak removal using layer priors. In *CVPR*, pages 2736–2744, 2016.
  - ***DSC:*** Y. Luo, Y. Xu, and H. Ji. Removing rain from a single image via discriminative sparse coding. In *ICCV*, pages 3397–3405, 2015.
- Rain + Haze Removal Methods:
  - ***RESCAN+DCPDN***
  - ***RESCAN+AOD***
  - ***DID-MDN+DCPDN***
  - ***DID-MDN+AOD***

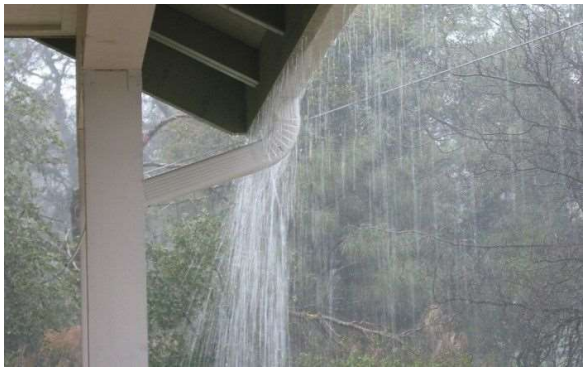
  where
  - ***DCPDN:*** H. Zhang and V. M. Patel. Densely connected pyramid dehazing network. In *CVPR*, pages 3194–3203, 2018.
  - ***AOD:*** B. Li, X. Peng, Z. Wang, J. Xu, and D. Feng. AOD-Net: Allin-one dehazing network. In *ICCV*, pages 4770–4778, 2017.

Part 2 presents more rain and rain-free image pairs in the RainCityscapes dataset.

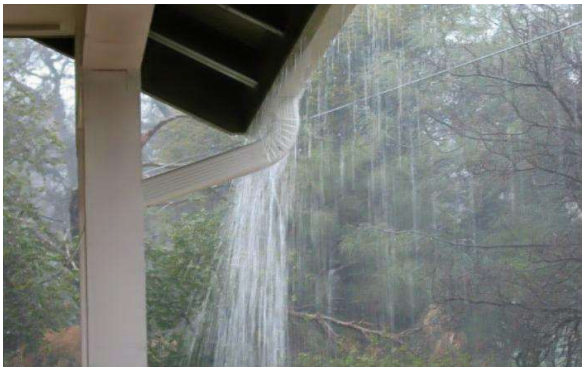
Part 3 presents an application of our method on improving vehicle detection in rain.

Part 4 presents additional experiments on our dataset and network.

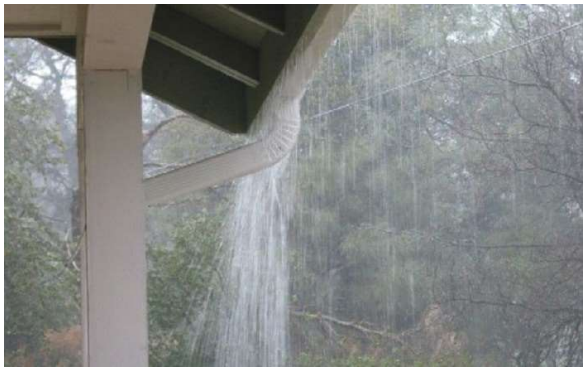
Part 1. Additional Comparison Results



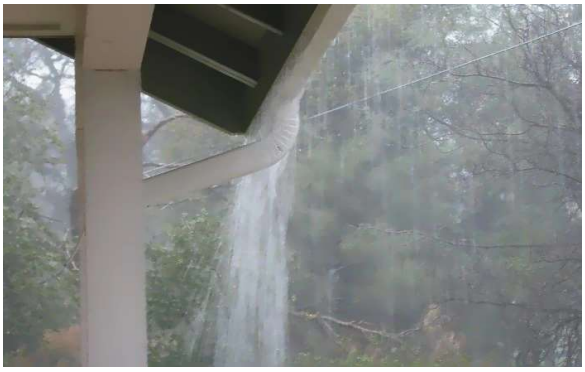
(a) input real photo



(b) DID-MDN

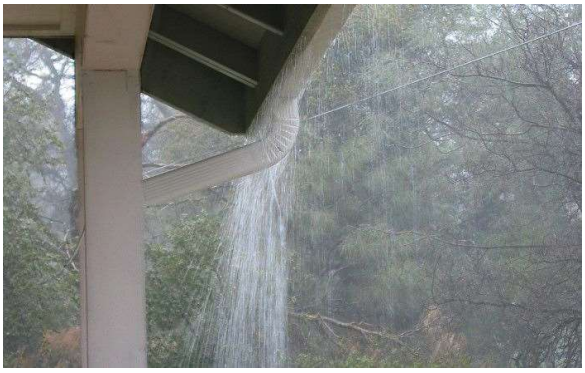


(c) RESCAN



(d) JBO

(e) GMMLP



(f) DSC

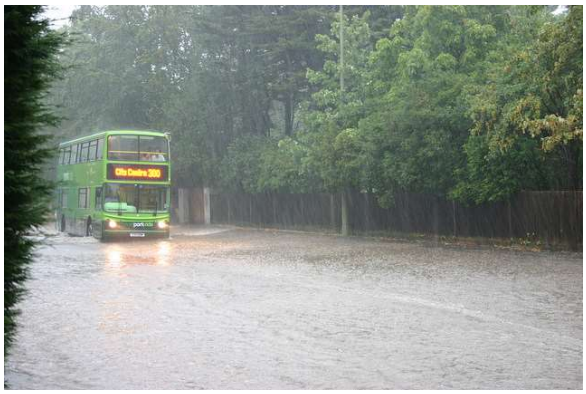
Figure 1: Visual comparison of single-image rain removal results on a real photo #1; see our result in the next figure.

(a) RESCAN+DCPDN (b) RESCAN+AOD

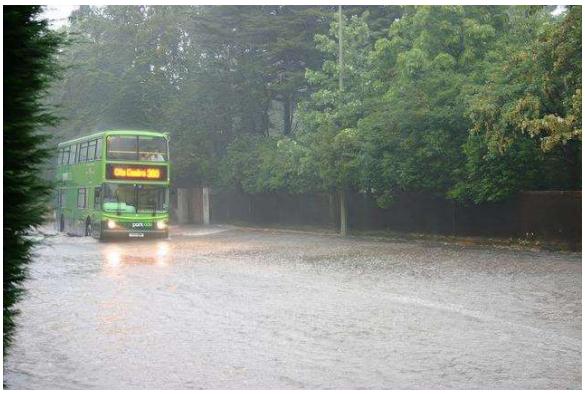
(c) DID-MDN+DCPDN (d) DID-MDN+AOD

(e) our result

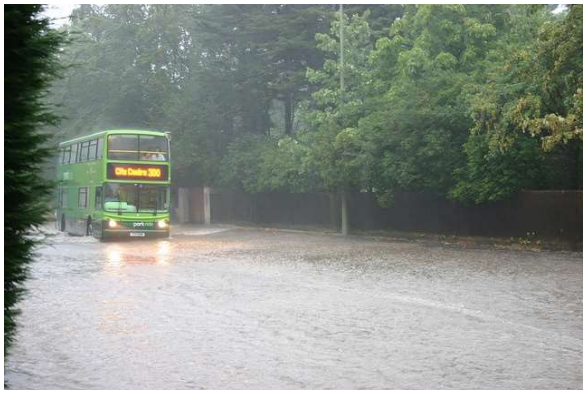
Figure 2: Visual comparison of single-image rain removal results on a real photo #1.



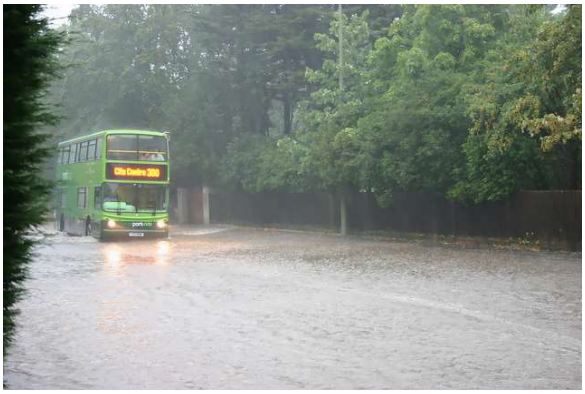
(a) input real photo



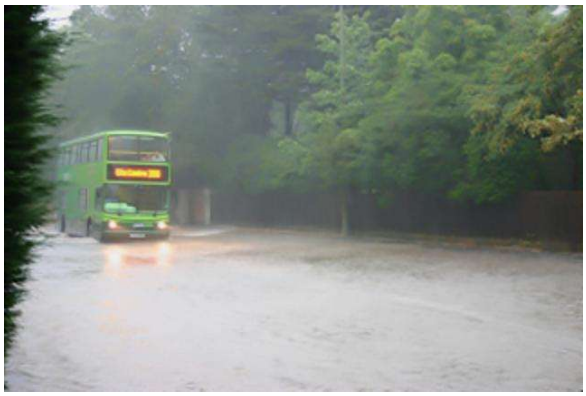
(b) DID-MDN



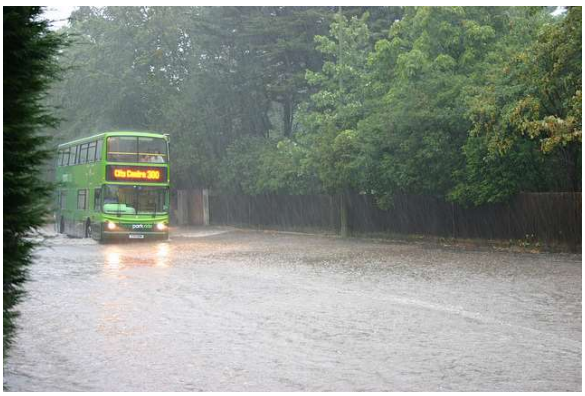
(c) RESCAN



(d) JBO



(e) GMMLP



(f) DSC

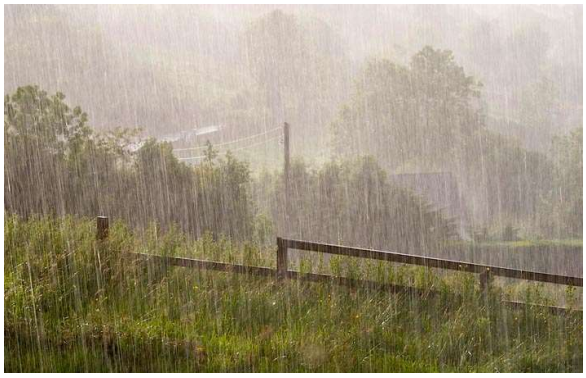
Figure 3: Visual comparison of single-image rain removal results on a real photo #2; see our result in the next figure.

(a) RESCAN+DCPDN (b) RESCAN+AOD

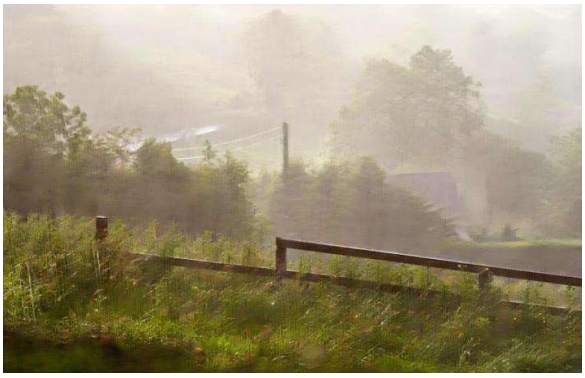
(c) DID-MDN+DCPDN (d) DID-MDN+AOD

(e) our result

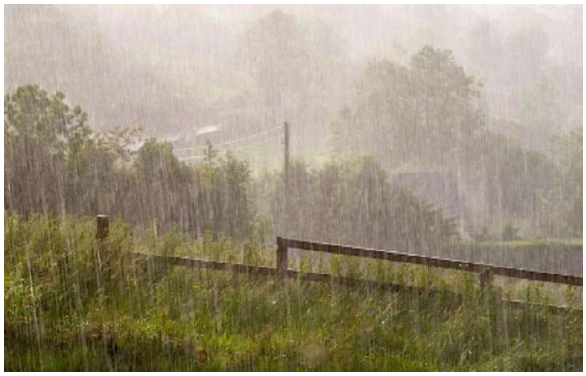
Figure 4: Visual comparison of single-image rain removal results on a real photo #2.



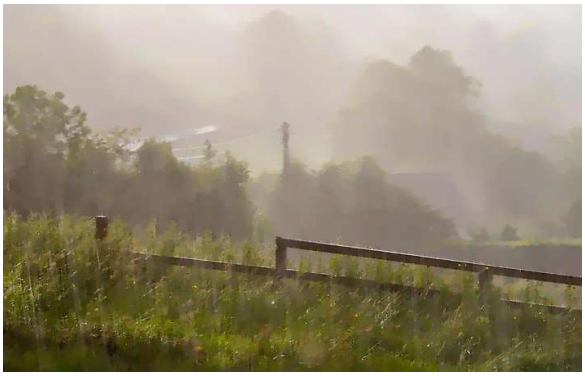
(a) input real photo



(b) DID-MDN

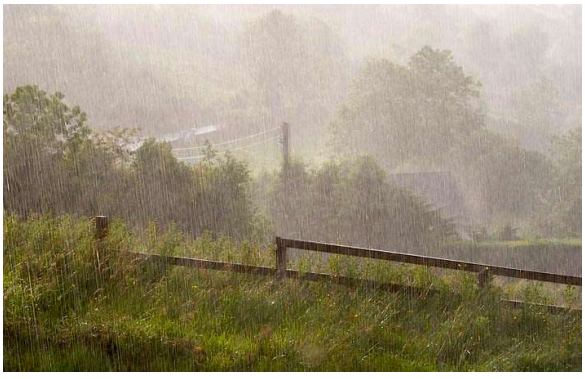


(c) RESCAN



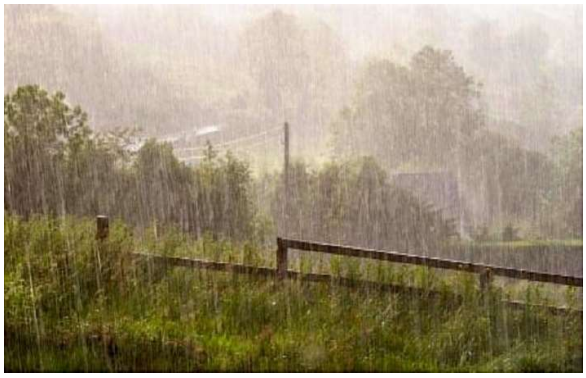
(d) JBO

(e) GMMLP

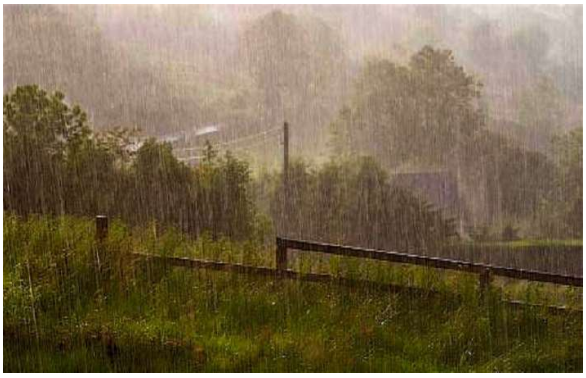


(f) DSC

Figure 5: Visual comparison of single-image rain removal results on a real photo #3; see our result in the next figure.

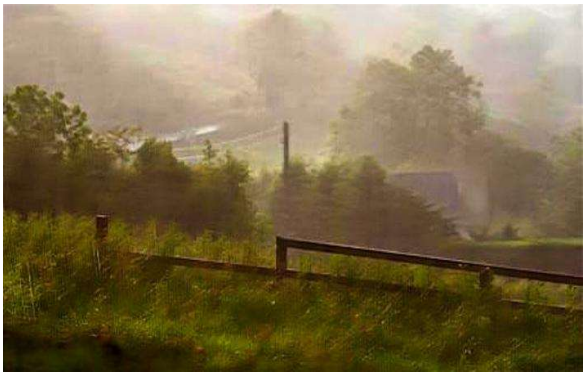


(a) RESCAN+DCPDN

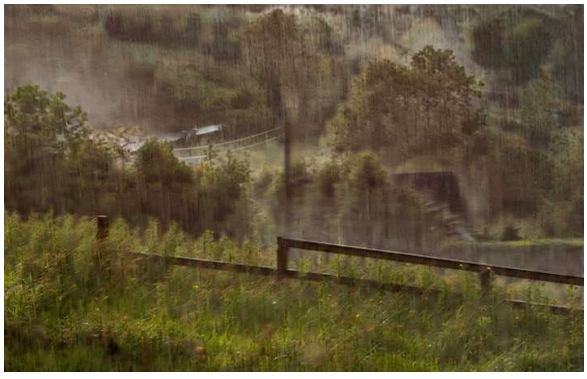


(b) RESCAN+AOD

(c) DID-MDN+DCPDN

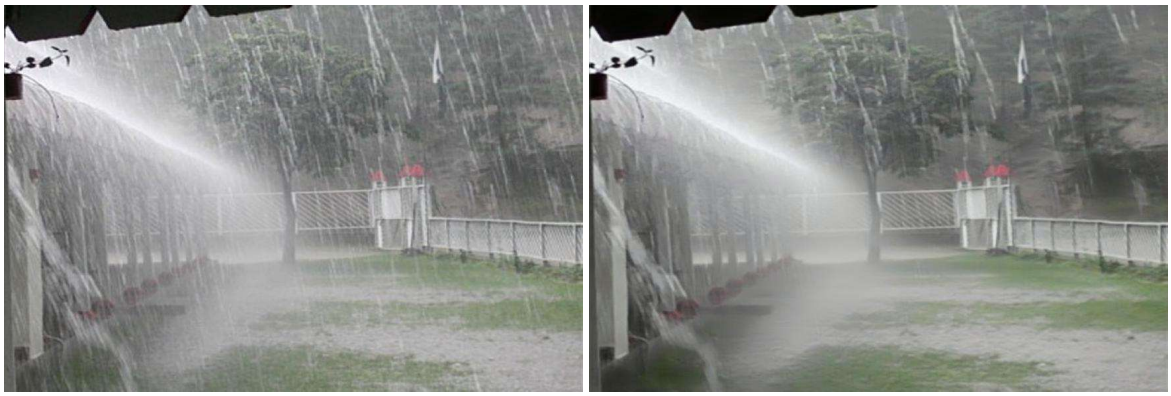


(d) DID-MDN+AOD



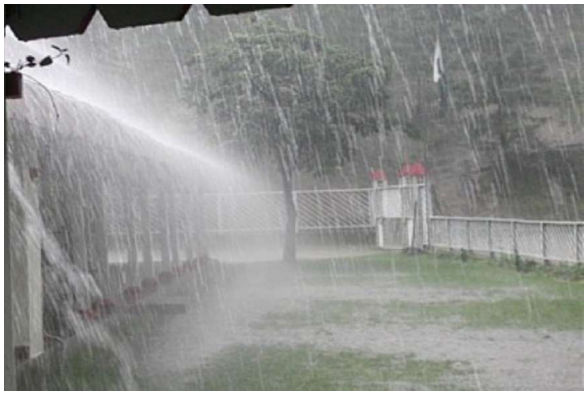
(e) our result

Figure 6: Visual comparison of single-image rain removal results on a real photo #3.

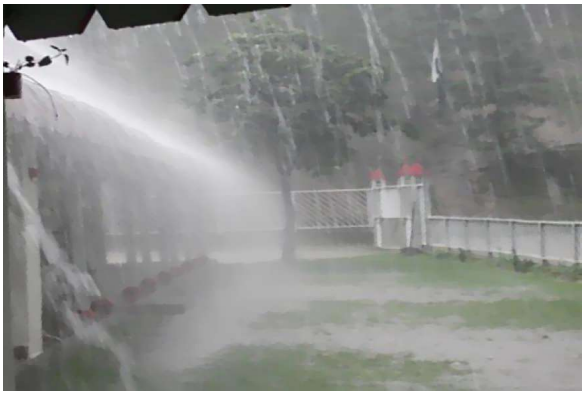


(a) input real photo

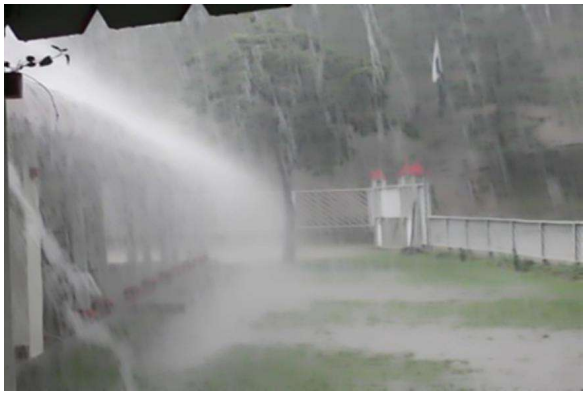
(b) DID-MDN



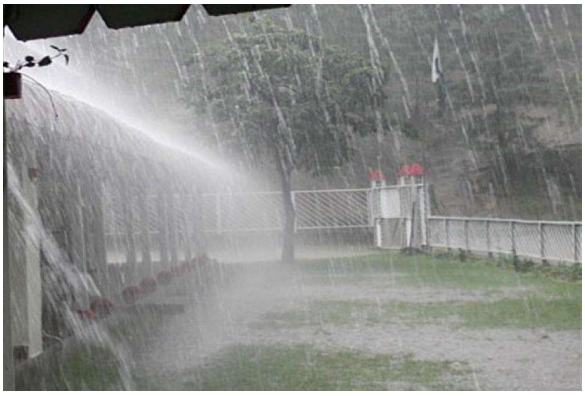
(c) RESCAN



(d) JBO

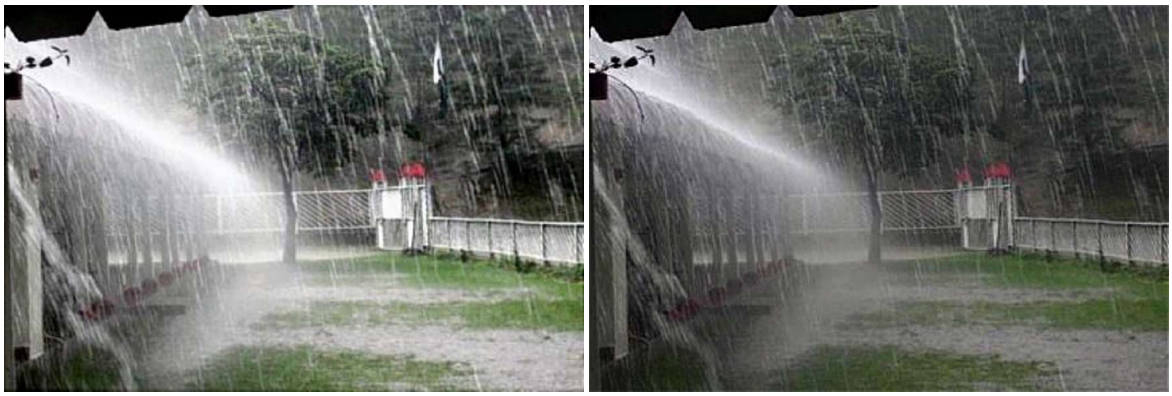


(e) GMMLP

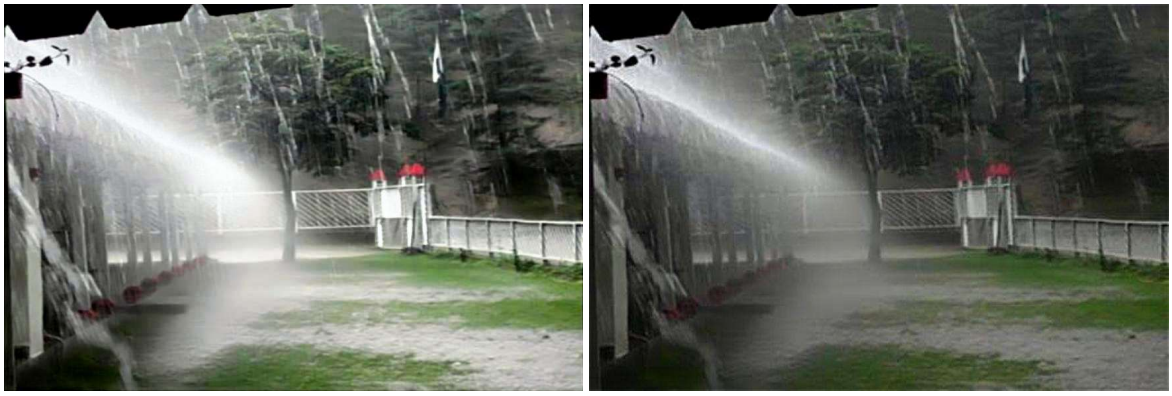


(f) DSC

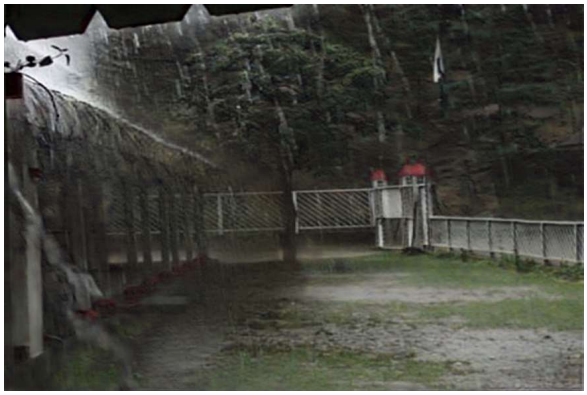
Figure 7: Visual comparison of single-image rain removal results on a real photo #4; see our result in the next figure.



(a) RESCAN+DCPDN (b) RESCAN+AOD

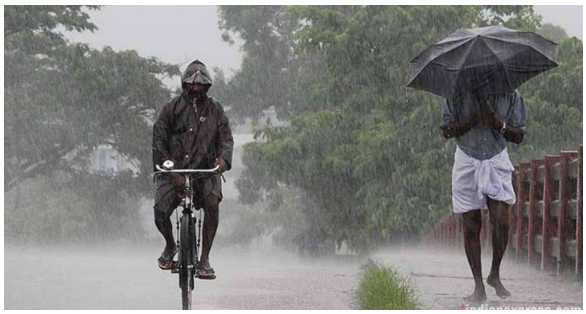


(c) DID-MDN+DCPDN (d) DID-MDN+AOD

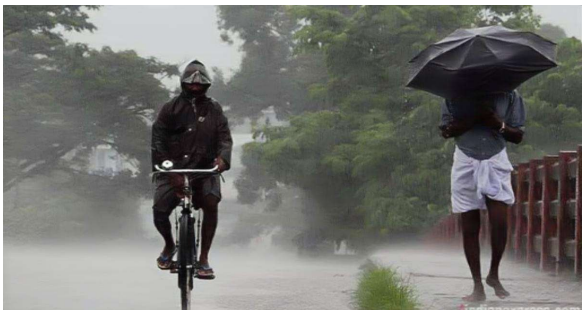


(e) our result

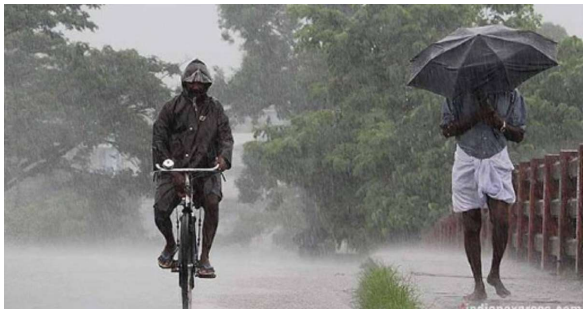
Figure 8: Visual comparison of single-image rain removal results on a real photo #4.



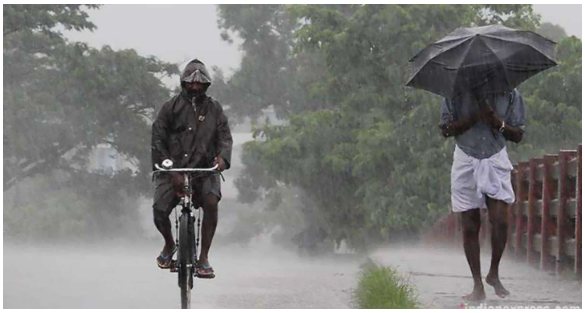
(a) input real photo



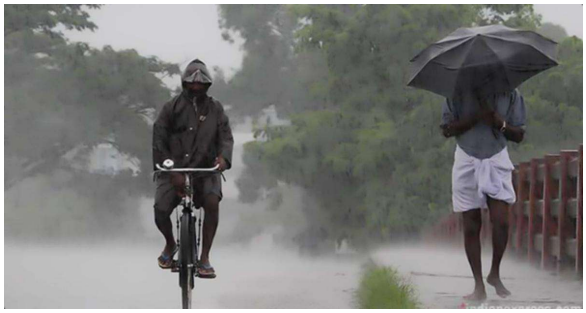
(b) DID-MDN



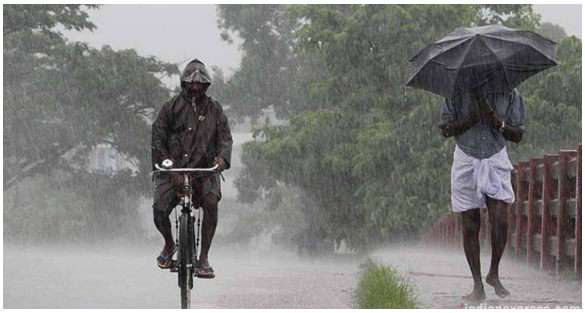
(c) RESCAN



(d) JBO



(e) GMMLP



(f) DSC

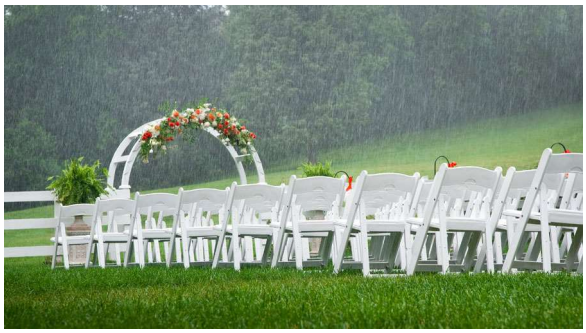
Figure 9: Visual comparison of single-image rain removal results on a real photo #5; see our result in the next figure.

(a) RESCAN+DCPDN (b) RESCAN+AOD

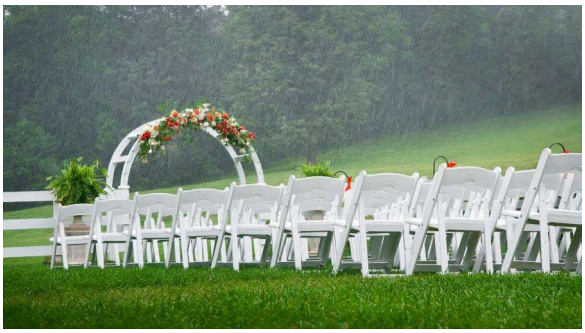
(c) DID-MDN+DCPDN (d) DID-MDN+AOD

(e) our result

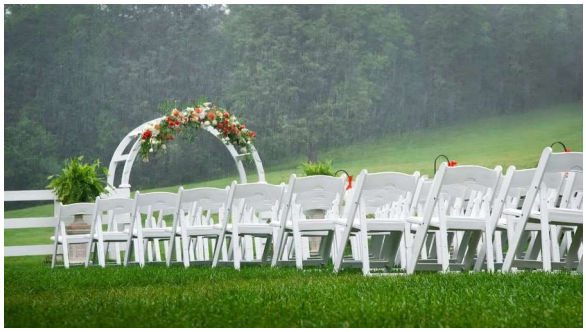
Figure 10: Visual comparison of single-image rain removal results on a real photo #5.



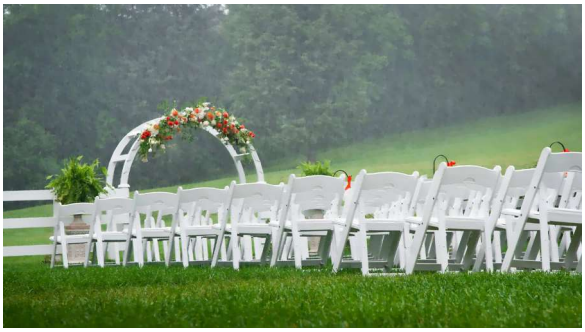
(a) input real photo



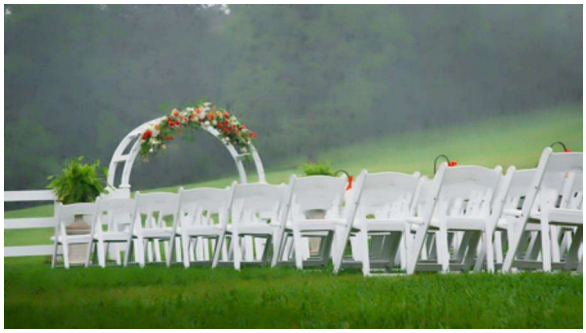
(b) DID-MDN



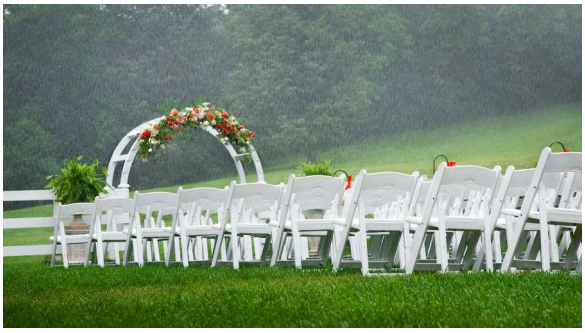
(c) RESCAN



(d) JBO

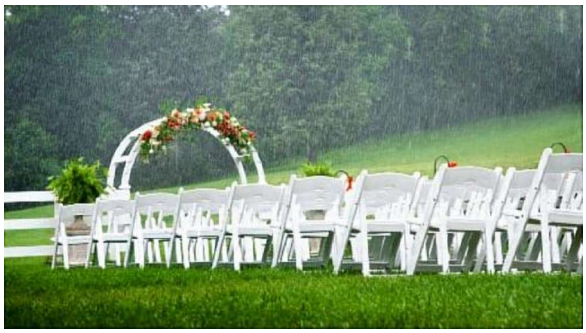


(e) GMMLP

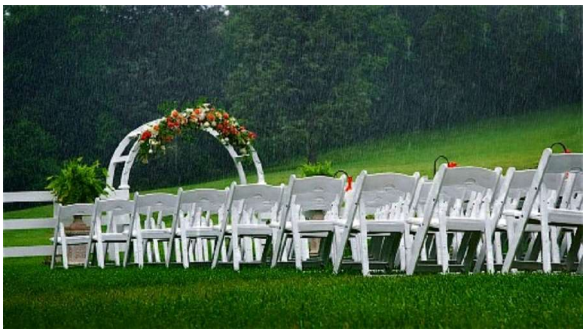


(f) DSC

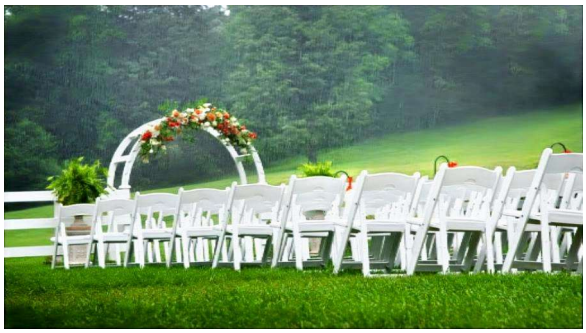
Figure 11: Visual comparison of single-image rain removal results on a real photo #6; see our result in the next figure.



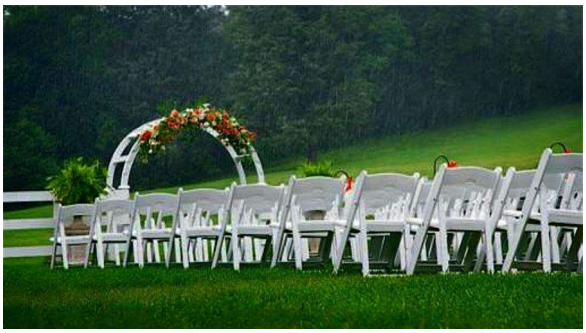
(a) RESCAN+DCPDN



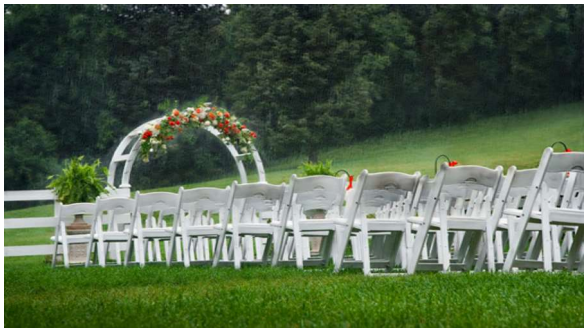
(b) RESCAN+AOD



(c) DID-MDN+DCPDN



(d) DID-MDN+AOD



(e) our result

Figure 12: Visual comparison of single-image rain removal results on a real photo #6.

(a) input real photo (b) DID-MDN

(c) RESCAN (d) JBO

(e) GMMLP (f) DSC

Figure 13: Visual comparison of single-image rain removal results on a real photo #7; see our result in the next figure. Courtesy of photographer Mac99 (Getty Images No. 182715405).

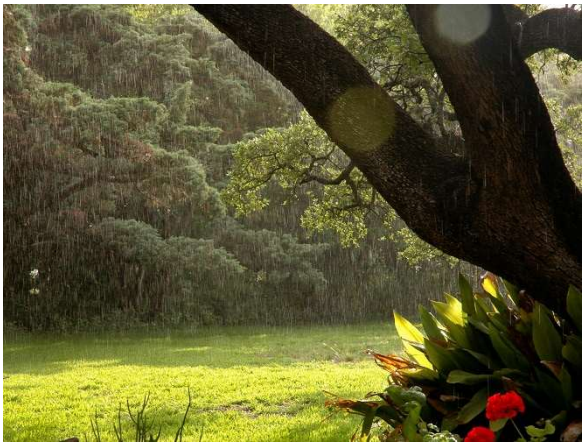
(a) RESCAN+DCPDN (b) RESCAN+AOD

(c) DID-MDN+DCPDN (d) DID-MDN+AOD

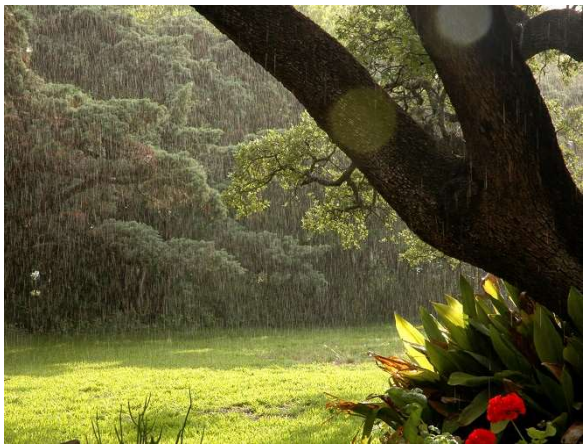
(e) our result

Figure 14: Visual comparison of single-image rain removal results on a real photo #7. Courtesy of photographer Mac99 (Getty Images No. 182715405).

(a) input real photo



(b) DID-MDN



(c) RESCAN

(d) JBO

(e) GMMLP

(f) DSC

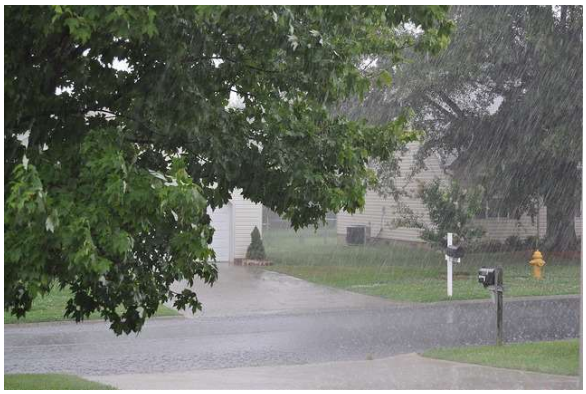
Figure 15: Visual comparison of single-image rain removal results on a real photo #8; see our result in the next figure.

(a) RESCAN+DCPDN (b) RESCAN+AOD

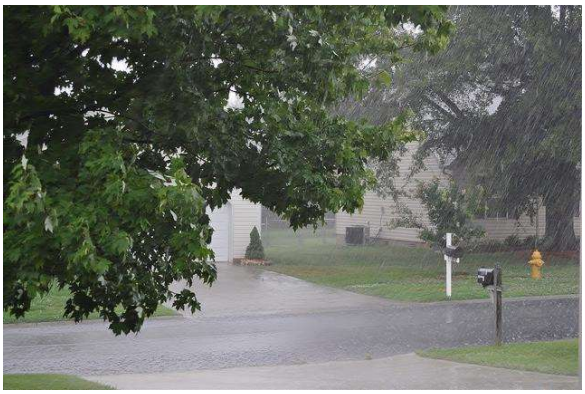
(c) DID-MDN+DCPDN (d) DID-MDN+AOD

(e) our result

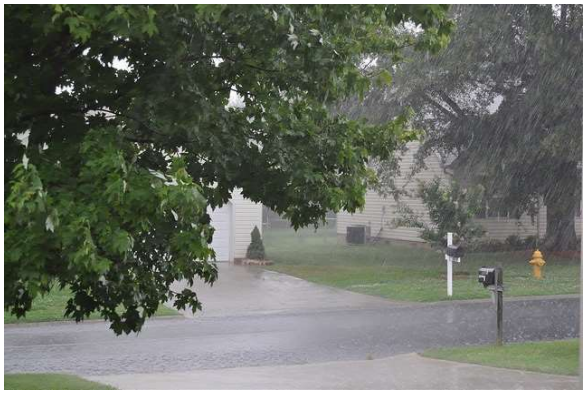
Figure 16: Visual comparison of single-image rain removal results on a real photo #8.



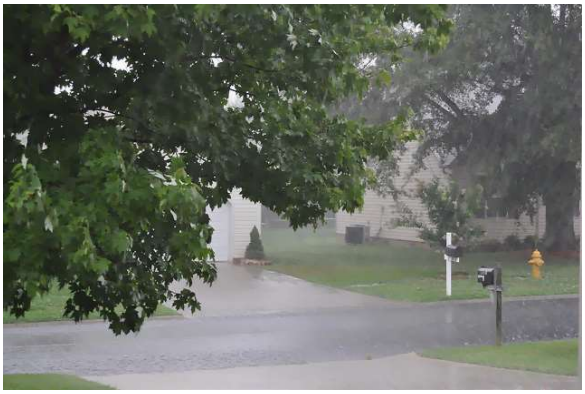
(a) input real photo



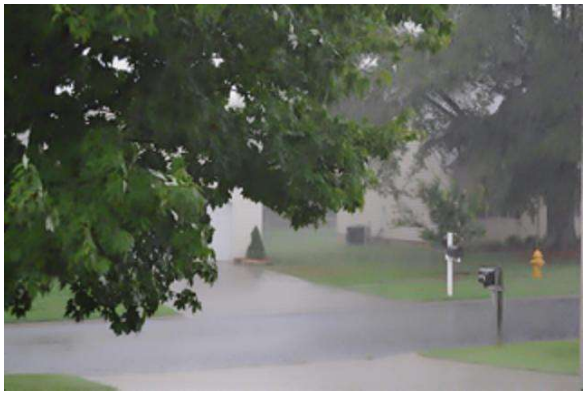
(b) DID-MDN



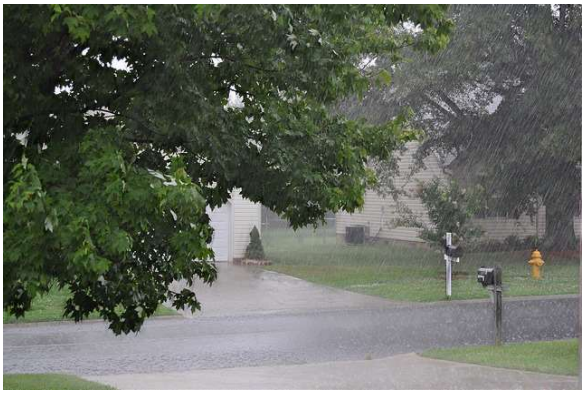
(c) RESCAN



(d) JBO

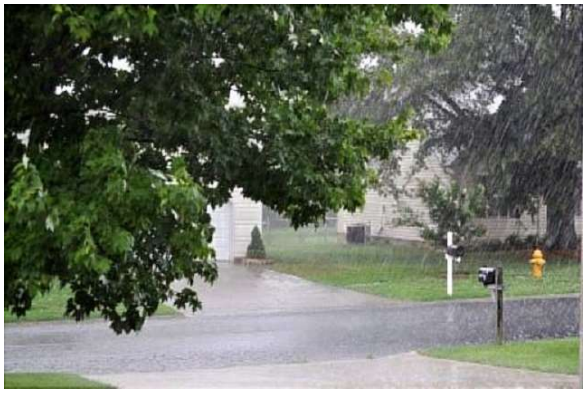


(e) GMMLP

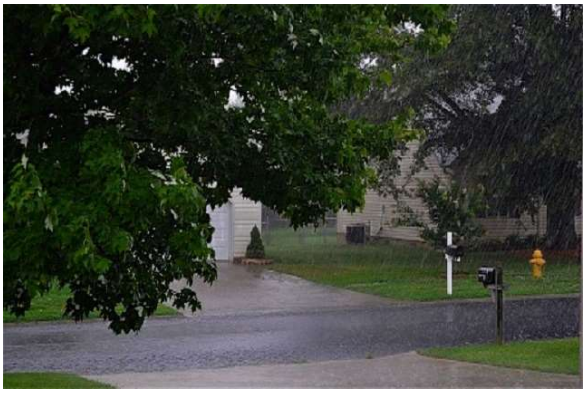


(f) DSC

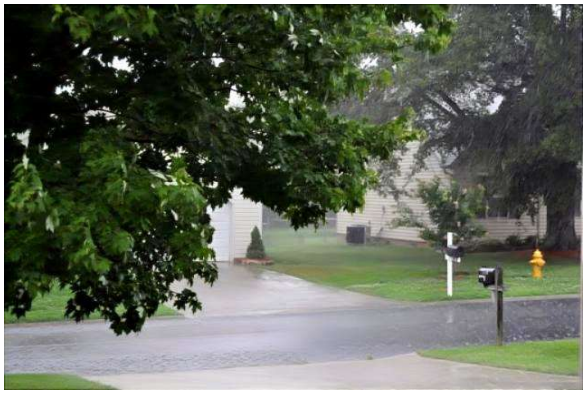
Figure 17: Visual comparison of single-image rain removal results on a real photo #9; see our result in the next figure.



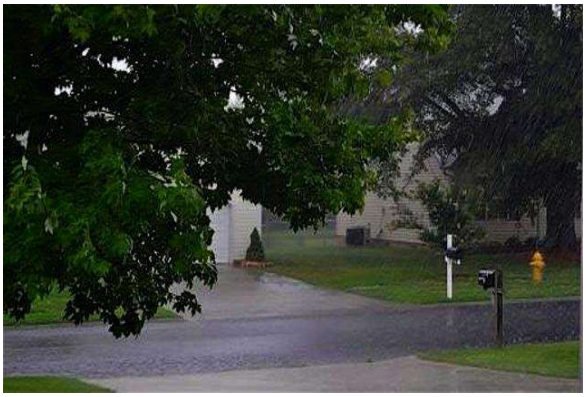
(a) RESCAN+DCPDN



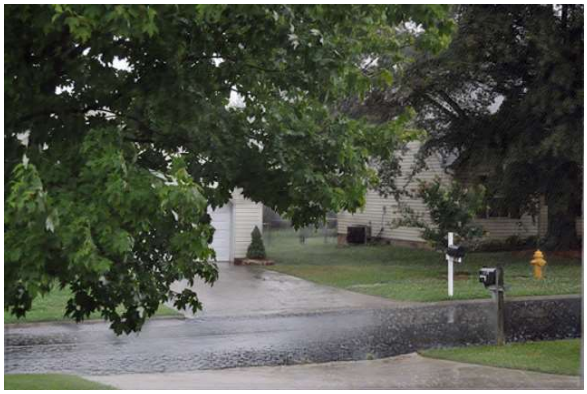
(b) RESCAN+AOD



(c) DID-MDN+DCPDN

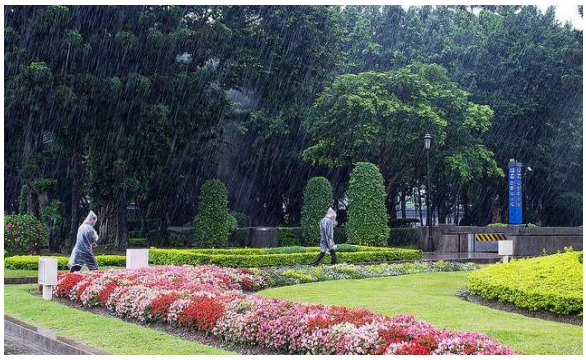


(d) DID-MDN+AOD

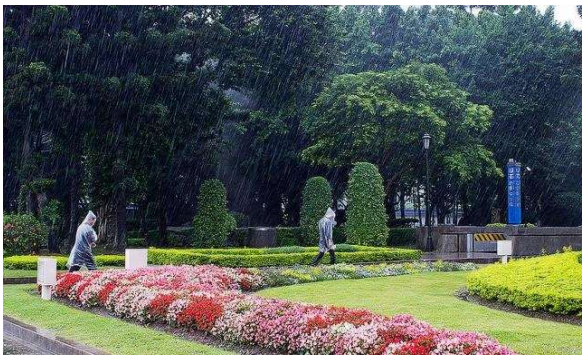


(e) our result

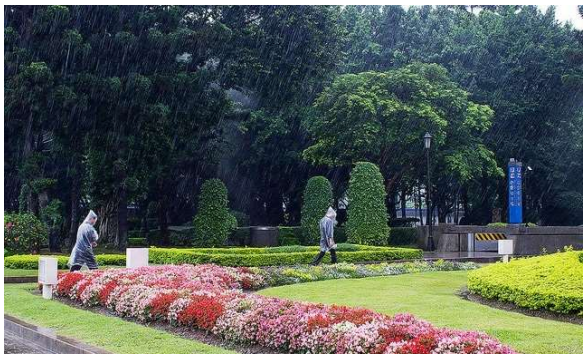
Figure 18: Visual comparison of single-image rain removal results on a real photo #9.



(a) input real photo



(b) DID-MDN



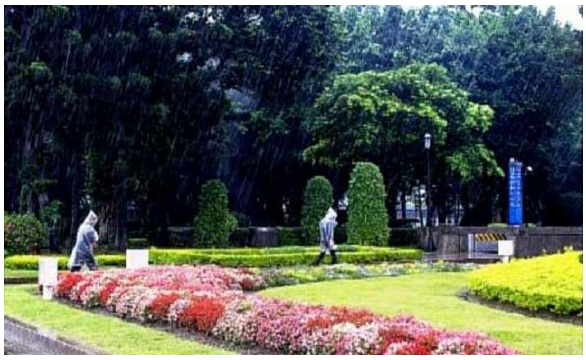
(c) RESCAN

(d) JBO

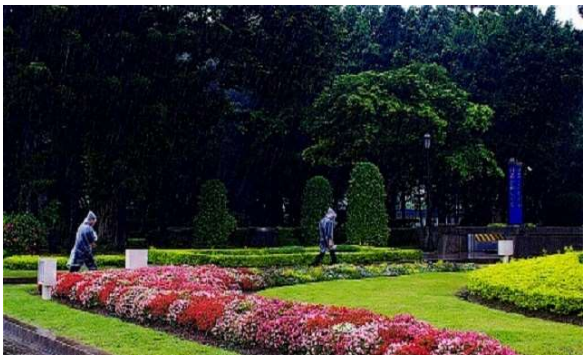
(e) GMMLP

(f) DSC

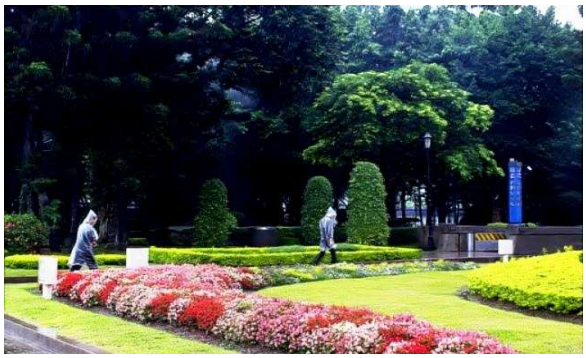
Figure 19: Visual comparison of single-image rain removal results on a real photo #10; see our result in the next figure.



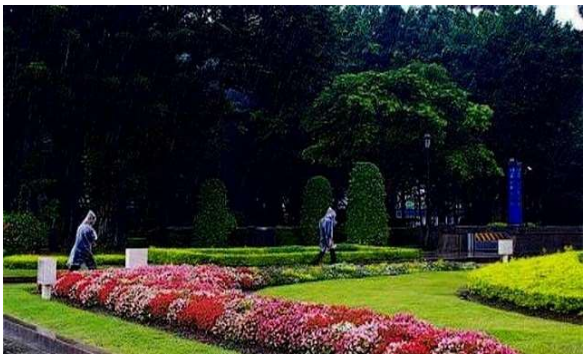
(a) RESCAN+DCPDN



(b) RESCAN+AOD



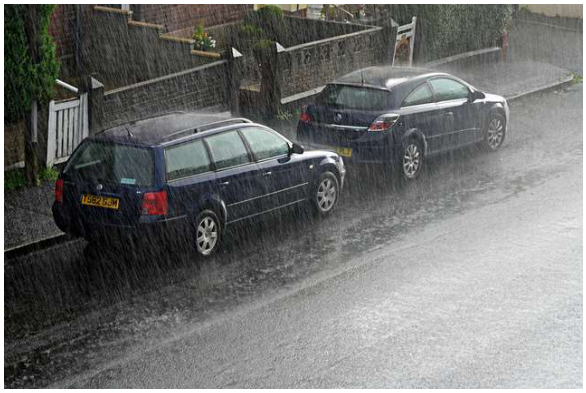
(c) DID-MDN+DCPDN



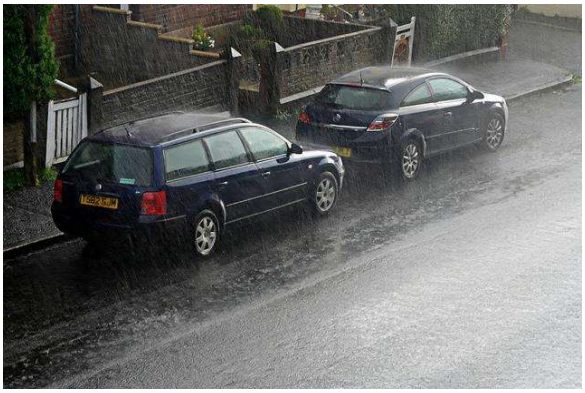
(d) DID-MDN+AOD

(e) our result

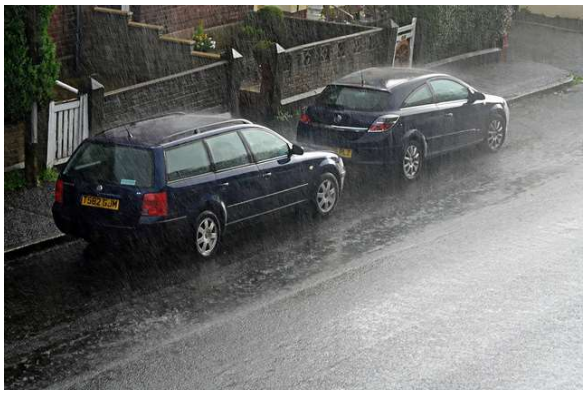
Figure 20: Visual comparison of single-image rain removal results on a real photo #10.



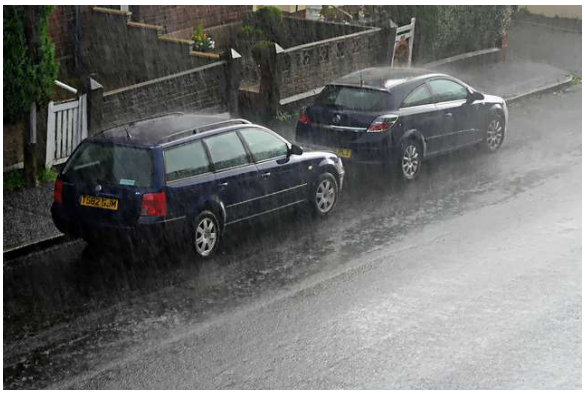
(a) input real photo



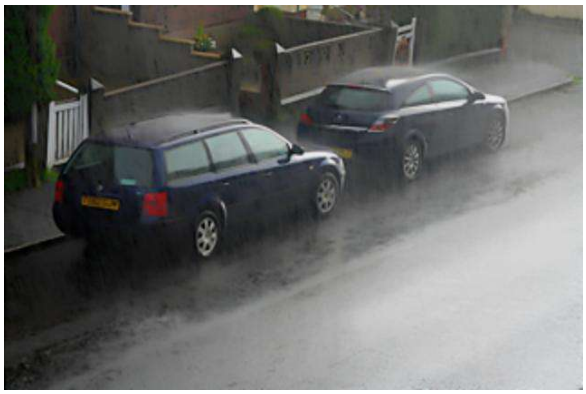
(b) DID-MDN



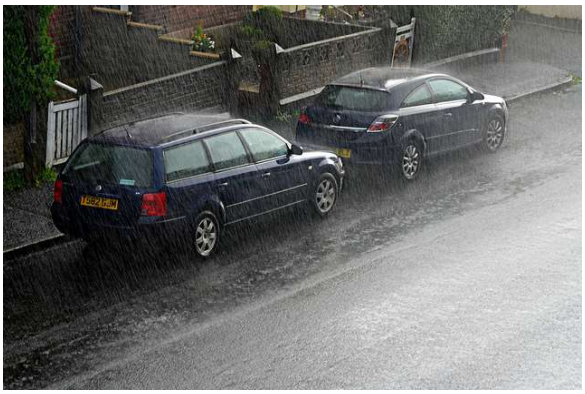
(c) RESCAN



(d) JBO

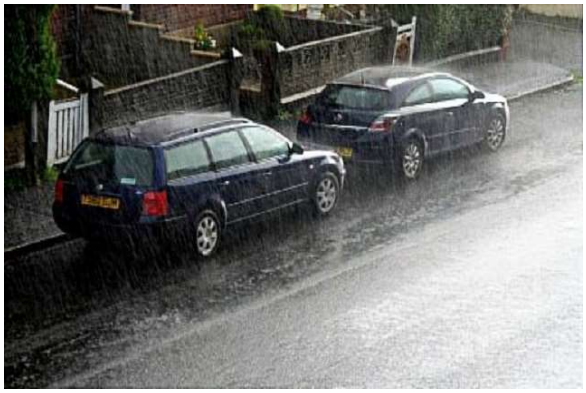


(e) GMMLP

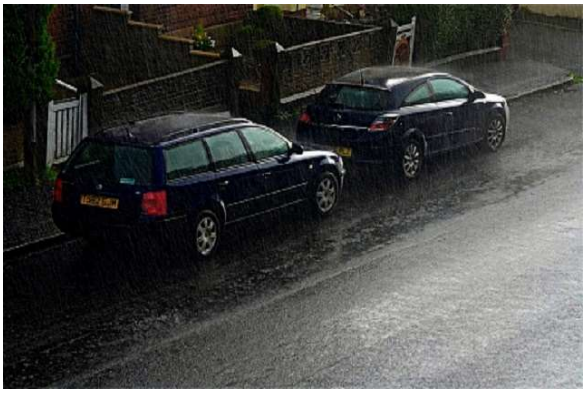


(f) DSC

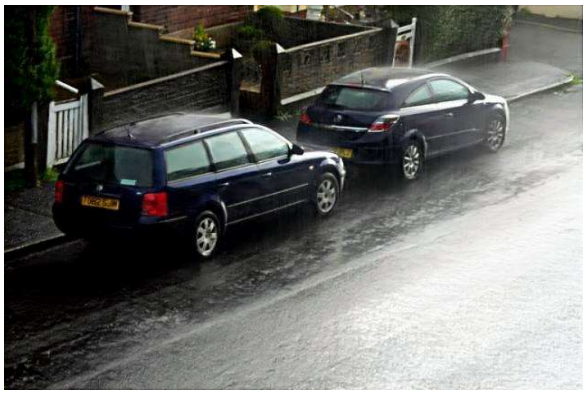
Figure 21: Visual comparison of single-image rain removal results on a real photo #11; see our result in the next figure.



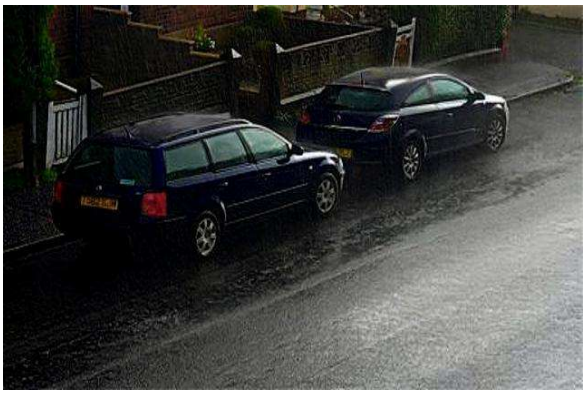
(a) RESCAN+DCPDN



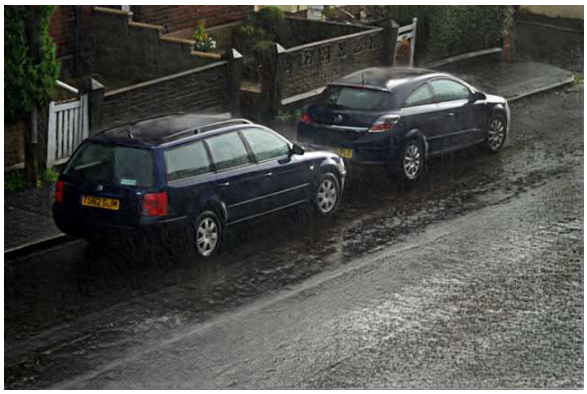
(b) RESCAN+AOD



(c) DID-MDN+DCPDN



(d) DID-MDN+AOD



(e) our result

Figure 22: Visual comparison of single-image rain removal results on a real photo #11.

Part 2. More Rain and Rain-free image pairs in our "RainCityscapes" dataset

(a) rain-free image

(b) rain image

Figure 23: Example rain-free and rain images in our RainCityscapes #1.

(a) rain-free image

(b) rain image

Figure 24: Example rain-free and rain images in our RainCityscapes #2.

(a) rain-free image

(b) rain image

Figure 25: Example rain-free and rain images in our RainCityscapes #3.

(a) rain-free image

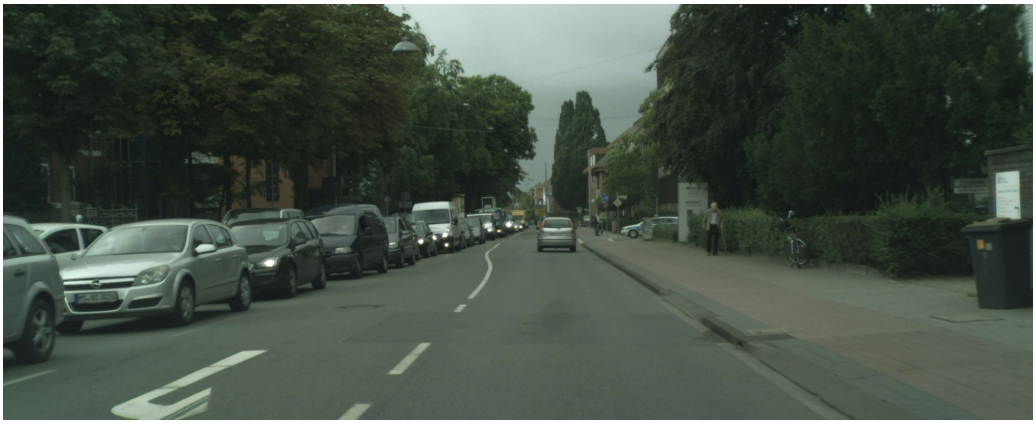
(b) rain image

Figure 26: Example rain-free and rain images in our RainCityscapes #4.

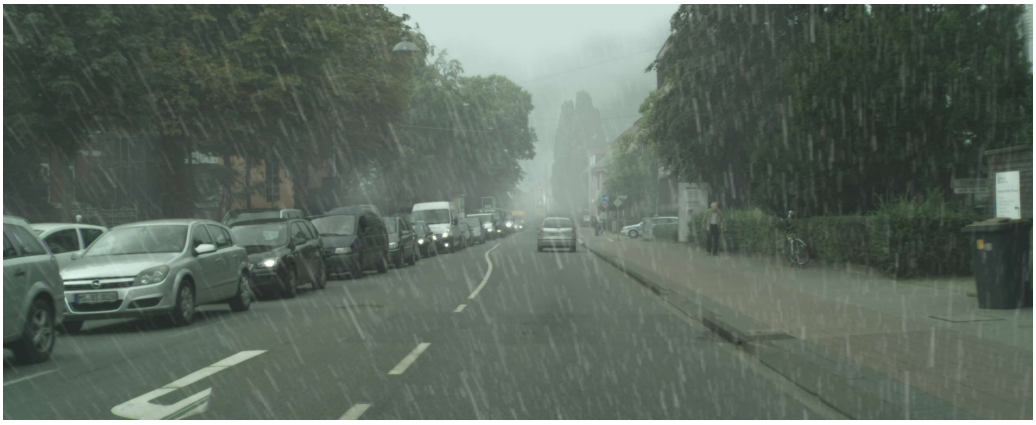
(a) rain-free image

(b) rain image

Figure 27: Example rain-free and rain images in our RainCityscapes #5.



(a) rain-free image



(b) rain image

Figure 28: Example rain-free and rain images in our RainCityscapes #6.

Part 3. Application: Vehicle Detection

The presence of rain would degrade the performance of vehicle detection. To evaluate how our method contributes to improve the accuracy of vehicle detection in rain, we downloaded the public code of SINet [1] and applied it to detect vehicles in rain images, in rain-free images produced from our method, and in rain-free ground-truth images inside the RainCityscapes dataset.

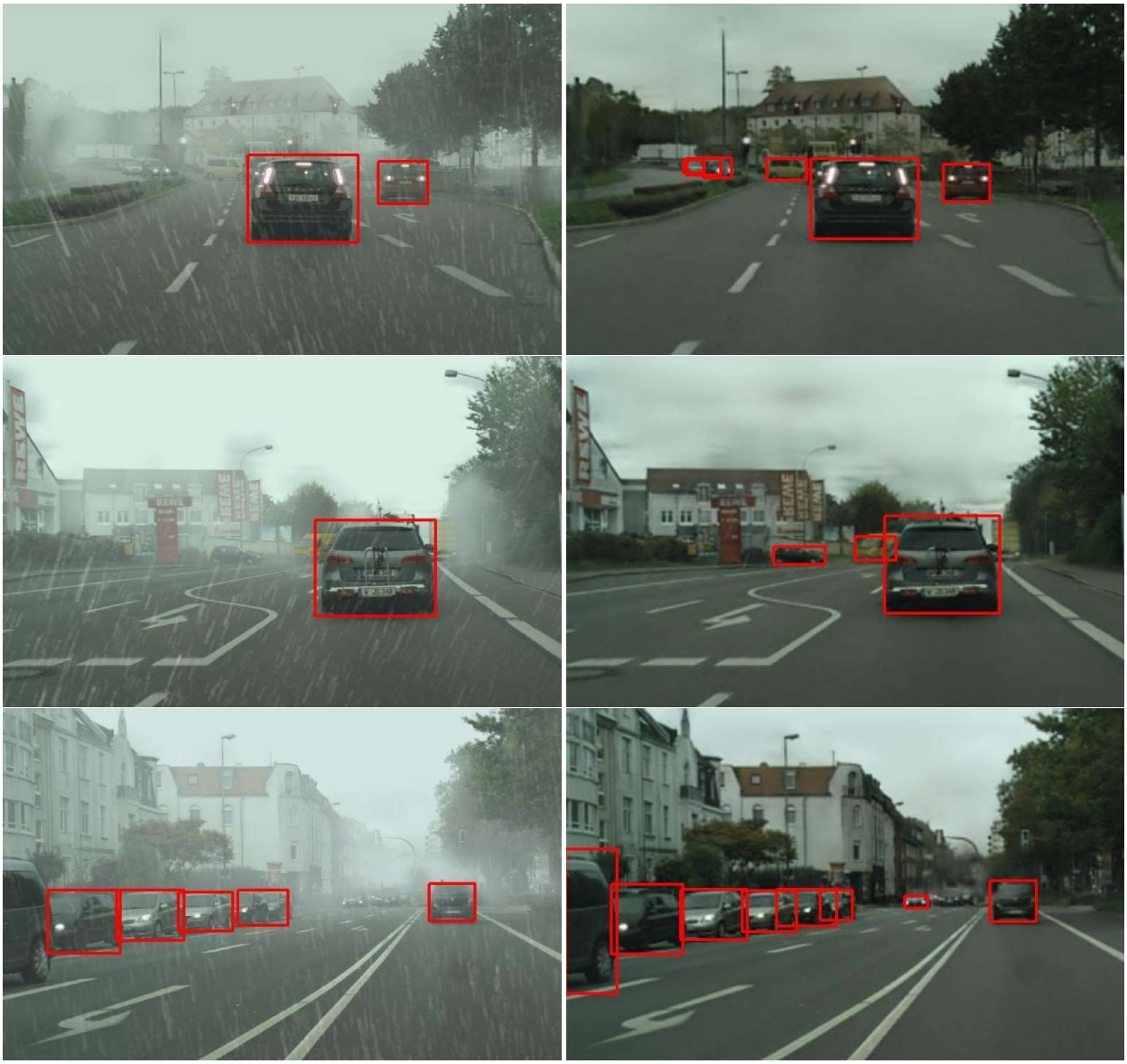
Table 1: Vehicle detection results. The performance is measured by average precision. A larger average precision indicates a better result.

method	car	bus
rain images	43.89%	56.63%
rain-free images (ours)	63.99%	78.95%
rain-free images (ground truth)	74.29%	84.34%

We trained the vehicle detection network on the training set of Cityscapes (2975 images), where the images are rain-free. Then we used the trained model to detect vehicles in the testing set of the RainCityscapes dataset (1188 images), including rain images, rain-free images produced from our method, and rain-free ground-truth images. Table 1 above reports the results, showing that our method can help improve the performance of vehicle detection by removing the rain streaks and fog from the rain images. In addition, it also helps to enhance the visibility of objects in the scene. This result shows that our rain removal method has potential for surveillance, autonomous driving, and driver assistance in rainy days. We will illustrate the visual comparison results in the following images.

References

[1] X. Hu, X. Xu, Y. Xiao, H. Chen, S. He, J. Qin, and P.-A. Heng. SINet: A scale-insensitive convolutional neural network for fast vehicle detection. *IEEE Transactions on Intelligent Transportation Systems*, 20(3):1010–1019, 2019. 31



(a) vehicle detection on rain images

(b) vehicle detection on rain-free images (ours)

Figure 29: Vehicle detection results on rain images and rain-free images produced from our method.

Part 4. Additional Experiments on Our Dataset and Network

Comparisons using different training data. We trained our deep network separately on RainCityscapes and Rain100H, and tested them on real images. From Figure 30 below, we can see that the network trained on Rain100H may miss the fog that comes with the rain, while the network trained on RainCityscapes can remove both rain streaks and fog, thus clearly showing the advantage of RainCityscapes.

input real photo | Rain100H | RainCityscapes

Figure 30: Visual comparison results on real photos. We thank the photographer Mac99 for providing the input real photo at the first row (Getty Images No. 182715405).

The size of the depth map. We performed experiments using the depth maps of different sizes. The PSNR and SSIM values on RainCityscapes dataset for sizes of 1/2, 1/4, and 1/8 of the image (256×512) are (30.04, 0.9525), (30.06, 0.9530), and (29.96, 0.9525), respectively. To trade off between the computation and memory consumption, we thus chose to use a quarter-width depth map in our network.