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Transforming Traffic Surveillance Cameras into Intelligent Sensors: A Machine-Learning Approach for Cost-Effective, High-Quality Monitoring

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- Motivation and Scope
- Methodology Overview
- Automated Data Acquisition
- Algorithm
- Results
- Conclusions and Future Work

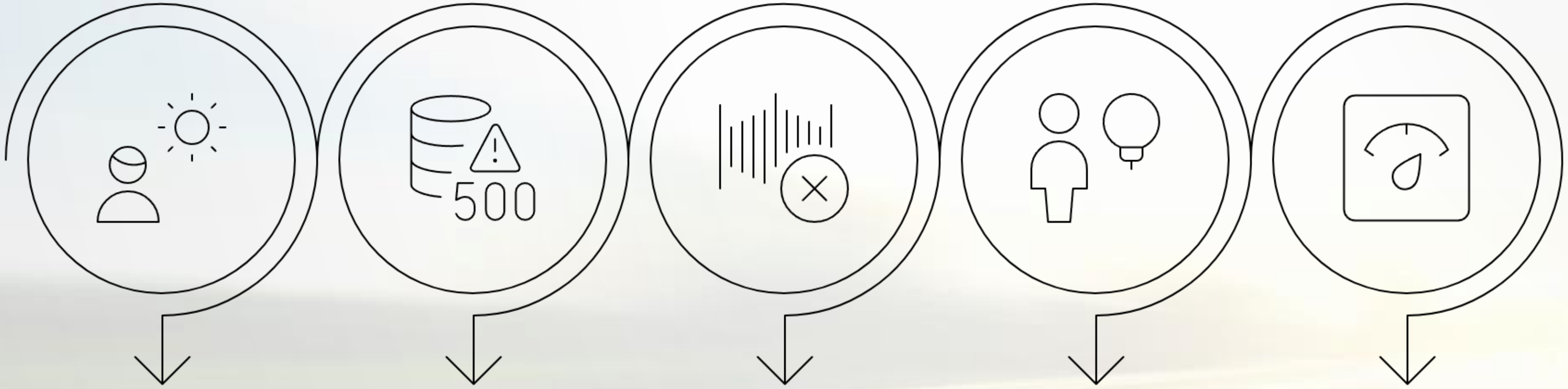
Physical and Environmental Constraints of Camera Systems

1. Low Resolution and Frame Rate/Motion Blur
2. Unknown Camera Configuration Parameters
3. Non-Optimal Field of View and Perspective Distortion
4. Limited Dynamic Range
5. Network & Compression Artifacts
6. Environmental Visibility Limitations /Nighttime / low-light and adverse weather

- **Opportunity:**
  - **Most corridors already have deployable CCTV cameras**
  - **Video cameras are widely used and information-dense**

CCTV: closed circuit television

Algorithmic and Developmental Constraints in ML-Based Detection



Dataset Bias

Training datasets favor clear conditions and lack diversity.

Domain Generalization

Models perform poorly in real-world deployments.

Sensitivity to Noise

Detection accuracy drops with sensor noise.

Illumination Dependence

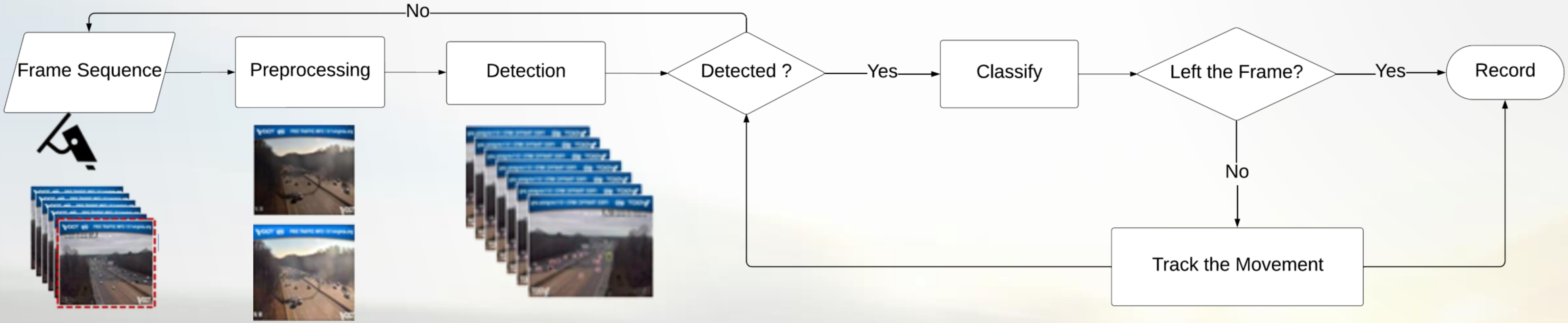
Models lack robustness under brightness variation.

Computational Trade-Offs

Robustness requires heavier models, reducing efficiency.

Machine-learning algorithm with advanced preprocessing

Methodology Overview



1 Detection

- Provides accurate detection and vehicle counting over extended periods.
- Optimized for favorable conditions (e.g., daytime with clear weather).

2 Classification

- Currently supports basic vehicle classification:

1. Auto
2. Truck (All Types of Truck, Pickup truck, Van)

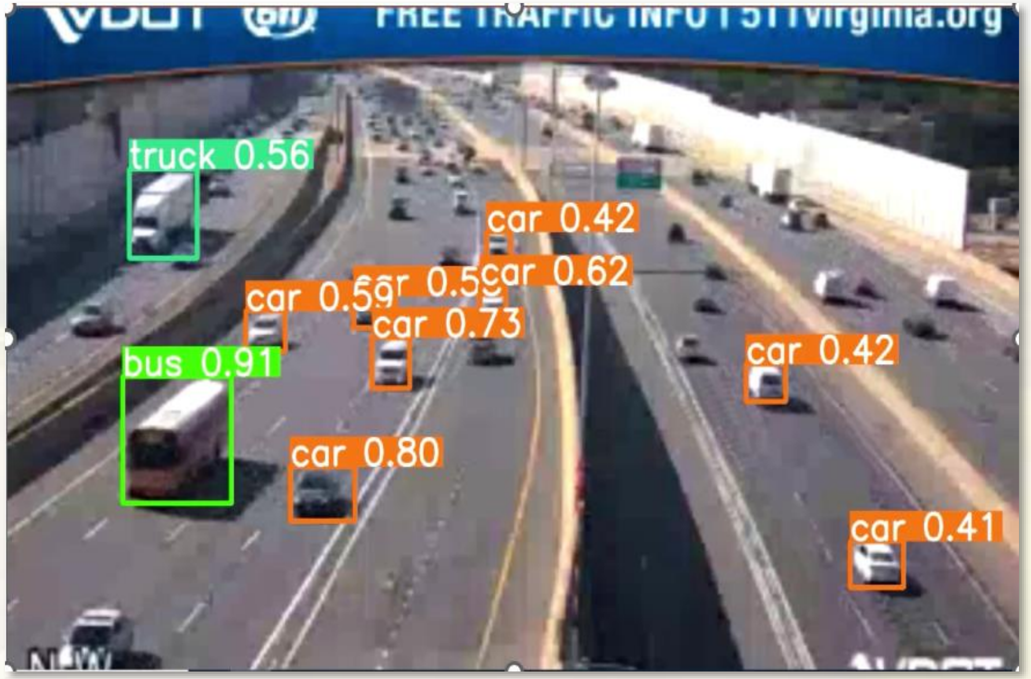
3 Directional

- Automatically determine the direction of travel.

4 Optimization

- Image processing techniques to increase image quality:
  - Challenging weather conditions
  - Low-light scenarios, including dusk and nighttime
  - Lens-related issues (e.g., droplets or dust)

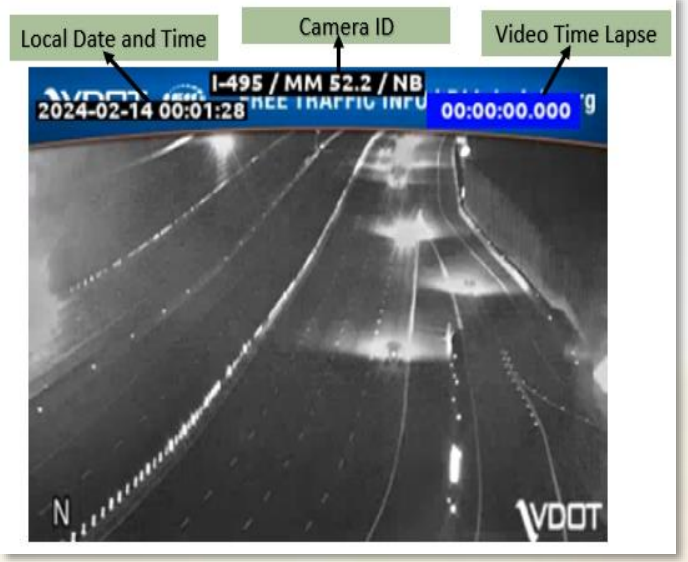
- **State of the Art Model** YOLOv8 provides real-time object detection with high accuracy and speed
- **One-Stage Detector:** Directly predicts bounding boxes and class probabilities
- **Multi-Class Capability:** Can detect and classify different vehicle types (cars, trucks)
- **Deployment Ready:** Lightweight for real-time traffic monitoring.
- **Training:** Pre-trained on COCO datasets
- **Development System:** Microsoft Windows 11 \ AMD Ryzen 5 6600H \ 63.2 GB RAM \ NVIDIA GeForce RTX 3050 Laptop GPU



YOLOv8 detection on a highway scene. Multiple vehicle classes labeled with confidence scores.

YOLOV8: You Only Look Once Version 8\ COCO: Common Objects in Context

Network & Sites	CCTV on primary gantries across Northern Virginia commuter corridors
24/7 Capture & Sync	Continuous RTSP with FFmpeg / Clocks synchronized; Local timestamps embedded in filenames and metadata
Segmentation & Encoding	Stream is cut into 15-minute clips; CUDA for hardware-accelerated decode/encode
Parallel Processing	Multi-location capture workers run in parallel with retry/back; health checks for bitrate, FPS, and latency.
Quality Assurance	Automated flags black/blank frames, excessive jitter and drop-frame rates; alerts trigger re-capture
Output	Per-clip stores camera ID, with a consistent path schema: site id/YYYY/MM/DD/HH:MM/



On-frame metadata overlays (date/time, camera ID, mile-marker, direction, elapsed time) parsed per clip for synchronization

Example of low-quality data dropped during the quality check

RTSP: Real-Time Streaming Protocol\ **FFMPEG**: Fast Forward Moving Picture Experts Group

Frame Enhancement

Image Enhancement Techniques

- **Headlight Glare Control**
  - Highlight Masking
  - Local Tone Compression
- **Noise Attenuation**
  - Gaussian Smoothing
  - Non-Local Means
  - Bilateral Filtering
- **Illumination Normalization**
  - Gamma Mapping
  - CLAHE
- **Artifacts Detector**
  - Saturation Checks
  - Color-Shift Checks
- **Operating Principle**
  - Luminance Restoration
  - Adaptive Gating
- **Edge Restoration**
  - Unsharp Mask
  - Laplacian

Raw versus enhanced frames, showing improved contrast and clarity.

CLACHE: Contrast Limited Adaptive Histogram Equalization

Trajectory Estimation

Duplicate handling

Retain the highest-confidence detection per ID and merge short-lived duplicates.

Temporal buffer

Keep the last 10 centers per ID to smooth noise.

State labeling

Classify each track as approaching, moving away, or stationary.

Inputs

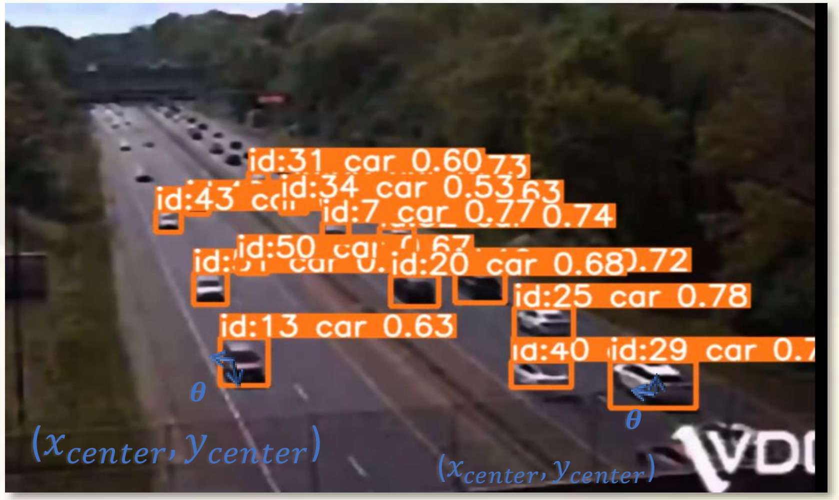
Per-frame detections with ID and box normalized by image size.

Position & direction

Use the bbox center and assign corridor direction from camera orientation.

Motion vector

Compute angle and step size from frame-to-frame center displacement; apply an adaptive threshold to ignore micro-jitter.



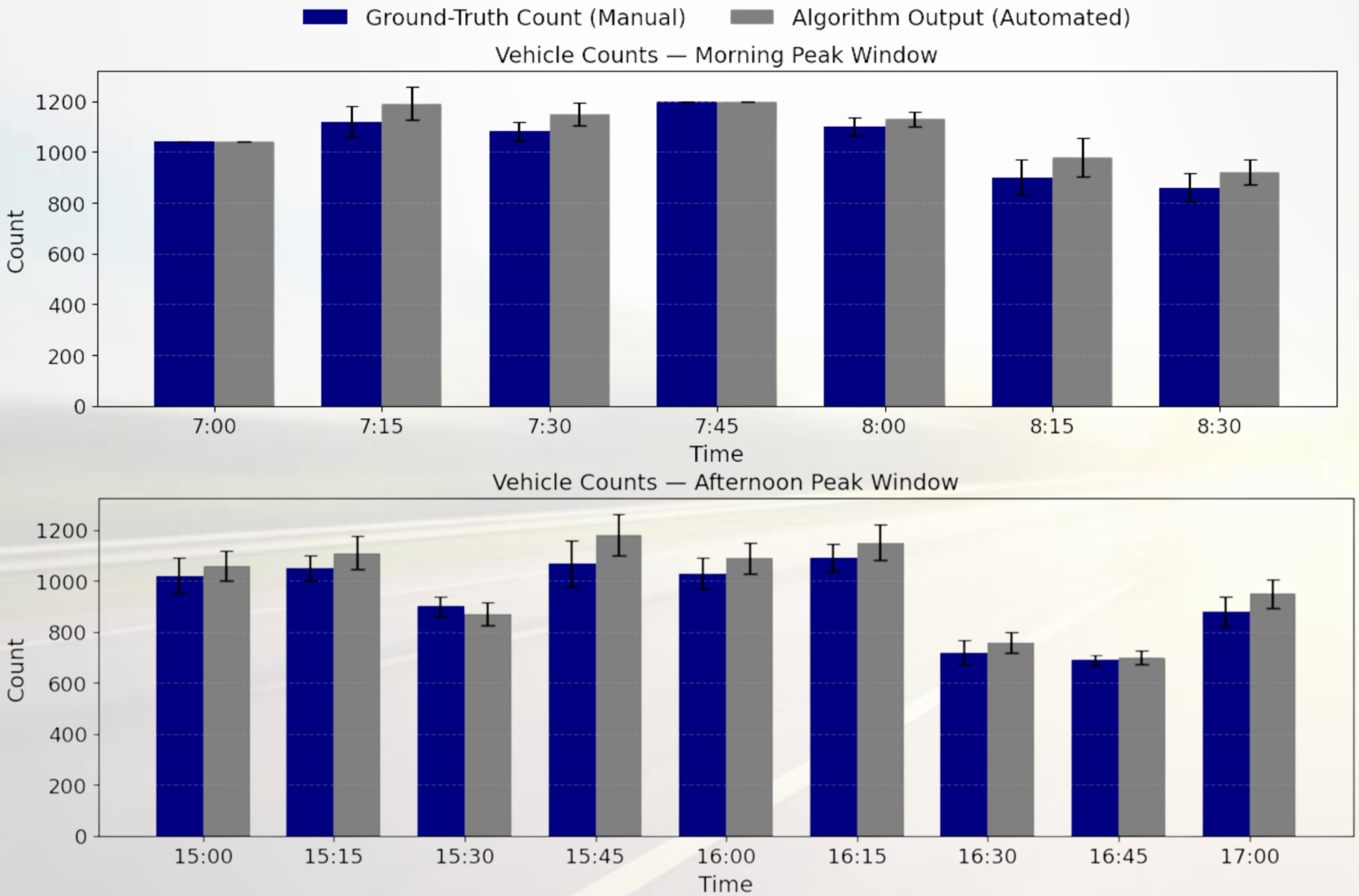
Trajectory detection from YOLO tracks. Motion vector analysis estimates each vehicle’s position, direction, and state.

Video Example of Detection and Classification with Enhancement Using Yolo

Evaluation of the Vehicle Detection Algorithm in Rainy Weather After Enhancement

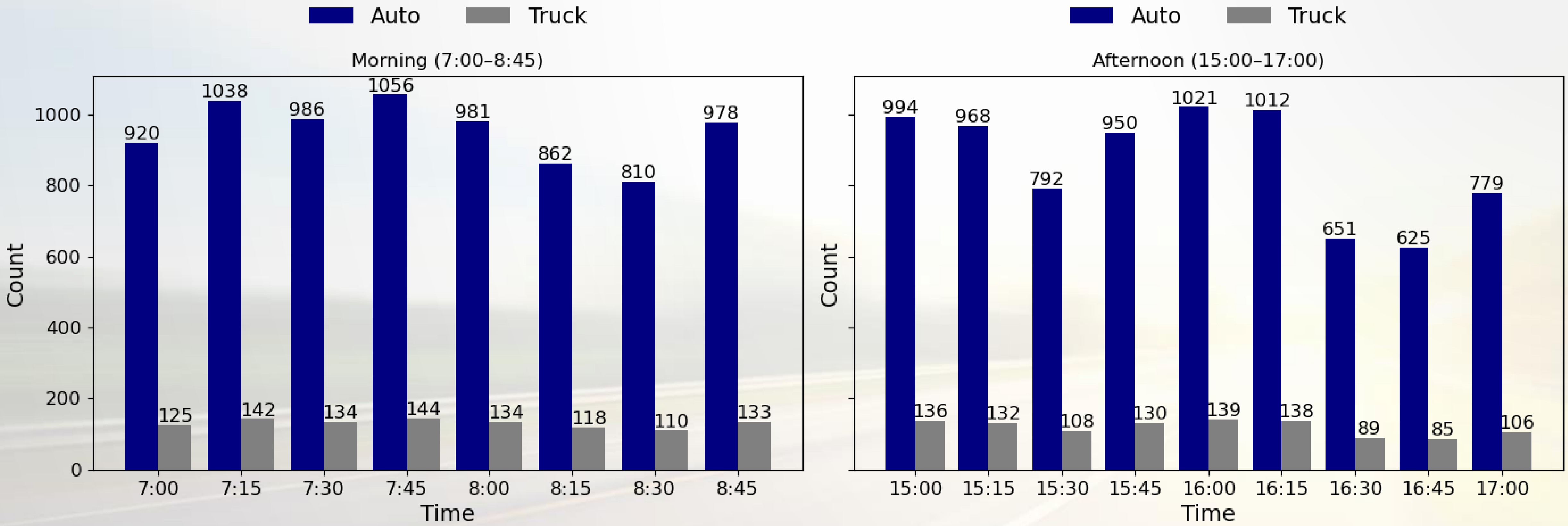
Example of Enhanced Images with Low Brightness and Contrast
Nighttime (left) and Dusk (right)

Results – Total Traffic Analysis



Comparative Analysis of Manual and Automated Vehicle Counts at Three Locations on I-66 Inside the Beltway (ItB) in VA. Morning Sessions (top) and Afternoon Sessions (bottom).

Note: Error bars represent variability in vehicle counts.

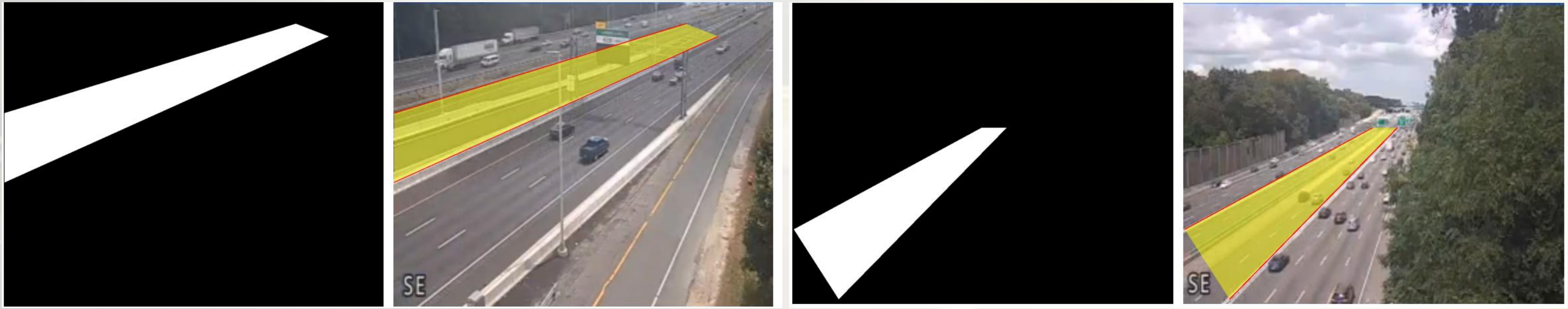


Auto vs. Truck counts by 15-minute interval, shown for (left) morning and (right) afternoon for I-495 in VA.

- **End-to-end automation**
  - Continuous acquisition → enhancement → YOLOv8 + BoT-SORT → trajectory reconstruction
- **Real-time, GPU-accelerated**
  - CUDA deployment, scalable across corridors
- **Robust preprocessing and Trajectory identification**
  - Illumination normalization, denoise/deblur, and glare control improve detector/track stability under adverse conditions
  - Ground plane mapping work without predefined ROIs, simplifying field deployment
- **Portable across cameras**
  - Handles varying orientations, focal lengths, and resolutions with minimal re-tuning
- **Cost-effective**
  - Uses existing CCTV
  - Reduces manual counts and hardware upgrades
  - Minimal retraining for new sites

Future Work

- Expand beyond basic vehicle classes (car, bus, truck)
  - **Light/medium/heavy trucks**
- Fine-tune and adjust the model for real-time deployment
- Lane-based traffic analysis based on different classes (Express Lane & GP Lane)



Lane Identification Mask and Overlay. Binary mask and color overlay for visual validation

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Questions/Comments

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