

# Range of Validity for System Outcomes

## 1. Vehicle Detection Accuracy

### 1.1 Optimal Operating Range

**Validity Range:** 92-97% detection accuracy **Conditions:**

- Clear weather (visibility > 5 miles)
- Daylight hours (sunrise + 1hr to sunset - 1hr)
- Moderate traffic density (5-25 vehicles/minute)
- Dry road conditions
- Temperature: 32°F to 85°F (-0°C to 29°C)
- Wind speed: < 25 mph

**Statistical Confidence:** 95% CI [91.2%, 97.8%] **Sample Size Required:**  $n \geq 1000$  detections for stable estimates

### 1.2 Degraded Performance Range

**Validity Range:** 78-91% detection accuracy **Conditions:**

- Light precipitation (< 0.1 inches/hour)
- Dawn/dusk periods (1 hour before/after sunrise/sunset)
- High traffic density (> 25 vehicles/minute) or very low (< 2 vehicles/minute)
- Wet road conditions with reflection
- Temperature: 15°F to 32°F or 85°F to 100°F
- Wind speed: 25-40 mph

**Statistical Confidence:** 95% CI [76.5%, 92.3%] **Expected Degradation:** 10-15% reduction from optimal

### 1.3 Minimum Acceptable Range

**Validity Range:** 60-77% detection accuracy **Conditions:**

- Moderate to heavy precipitation (0.1-0.5 inches/hour)
- Night conditions with artificial lighting
- Extreme traffic conditions (congestion or near-empty roads)
- Snow/ice on road surface

- Temperature: < 15°F or > 100°F
- Wind speed: > 40 mph
- Visibility: 1-5 miles

**Statistical Confidence:** 95% CI [58.2%, 79.1%] **Performance Warning:** System alerts recommend manual verification

## 1.4 System Failure Threshold

**Validity Range:** < 60% detection accuracy **Conditions:**

- Heavy precipitation (> 0.5 inches/hour)
- Dense fog (visibility < 1 mile)
- Severe weather (thunderstorms, blizzards)
- Equipment malfunction or obstruction
- Extreme temperatures: < 0°F or > 120°F

**System Response:** Automatic fallback to backup detection methods or system shutdown

## 2. Speed Measurement Accuracy

### 2.1 High Precision Range

**Validity Range:**  $\pm 1.5$  mph ( $\pm 2.4$  km/h) **Radar Measurement Conditions:**

- Single vehicle in detection zone
- Vehicle speed: 15-65 mph (24-105 km/h)
- Clear line of sight to radar sensor
- Dry conditions, minimal electromagnetic interference
- Vehicle approaching directly (angle < 15° from radar beam)

**Statistical Confidence:** 95% CI [ $\pm 1.2$  mph,  $\pm 1.8$  mph] **Calibration Frequency:** Monthly verification against reference standards

### 2.2 Standard Accuracy Range

**Validity Range:**  $\pm 2.5$  mph ( $\pm 4.0$  km/h) **Conditions:**

- Multiple vehicles present (sensor fusion algorithms active)
- Vehicle speed: 5-75 mph (8-121 km/h)
- Light precipitation or wet conditions

- Vehicle angle: 15-30° from radar beam
- Moderate electromagnetic environment

**Statistical Confidence:** 95% CI [ $\pm 2.1$  mph,  $\pm 2.9$  mph] **Data Fusion:** Combined visual tracking and radar measurements

## 2.3 Reduced Accuracy Range

**Validity Range:**  $\pm 4.0$  mph ( $\pm 6.4$  km/h) **Conditions:**

- High traffic density (multiple simultaneous vehicles)
- Vehicle speed:  $< 5$  mph or  $> 75$  mph
- Moderate precipitation or road spray
- Vehicle angle: 30-45° from radar beam
- Presence of large vehicles affecting radar reflection

**Statistical Confidence:** 95% CI [ $\pm 3.2$  mph,  $\pm 4.8$  mph] **Quality Flag:** Measurements marked with reduced confidence

## 2.4 Unreliable Measurement Range

**Validity Range:**  $> \pm 4.0$  mph or measurement unavailable **Conditions:**

- Vehicle speed:  $> 85$  mph (sensor saturation)
- Heavy precipitation affecting radar performance
- Vehicle angle:  $> 45^\circ$  from radar beam
- Significant electromagnetic interference
- Sensor obstruction or malfunction

**System Response:** Speed measurements flagged as unreliable or discarded

# 3. Multi-Vehicle Tracking Performance

## 3.1 Optimal Tracking Range

**Validity Range:** 88-95% track maintenance accuracy **Conditions:**

- 1-8 vehicles simultaneously in frame
- Clear visibility and lighting
- Vehicles maintaining consistent speeds ( $\pm 10$  mph variation)
- No occlusion or overlap between vehicles

- Frame rate: 25-30 fps consistently

**Track Persistence:** 95% of tracks maintained for full transit time **ID Consistency:** < 2% ID switches per tracking session

### 3.2 Moderate Tracking Range

**Validity Range:** 72-87% track maintenance accuracy **Conditions:**

- 9-15 vehicles simultaneously in frame
- Partial occlusion events (< 30% vehicle obscured)
- Variable lighting conditions
- Speed variations:  $\pm 20$  mph from average
- Frame rate drops: 20-24 fps

**Track Persistence:** 80% of tracks maintained **ID Consistency:** 3-8% ID switches per session

### 3.3 Challenging Tracking Range

**Validity Range:** 55-71% track maintenance accuracy **Conditions:**

- 15 vehicles simultaneously (congestion scenarios)
- Significant occlusion (30-60% vehicle obscured)
- Stop-and-go traffic conditions
- Poor visibility conditions
- Frame rate: 15-19 fps

**Track Persistence:** 65% of tracks maintained **ID Consistency:** 9-15% ID switches per session

### 3.4 Tracking Failure Threshold

**Validity Range:** < 55% track maintenance accuracy **Conditions:**

- Extreme congestion (vehicles stationary or < 5 mph)
- Complete occlusion events
- Frame rate: < 15 fps
- System overload conditions

**System Response:** Tracking algorithm switches to detection-only mode

## 4. Environmental Operating Ranges

## 4.1 Temperature Validity Ranges

### Optimal Performance

**Range:** 40°F to 75°F (4°C to 24°C)

- All sensors operate within specifications
- Battery life maximized
- Minimal thermal drift in measurements

### Acceptable Performance

**Range:** 15°F to 40°F and 75°F to 95°F (-9°C to 4°C and 24°C to 35°C)

- Performance degradation: 5-10%
- Increased power consumption
- Periodic recalibration required

### Degraded Performance

**Range:** 0°F to 15°F and 95°F to 110°F (-18°C to -9°C and 35°C to 43°C)

- Performance degradation: 15-25%
- Frequent recalibrations needed
- Possible intermittent sensor issues

### Critical Threshold

**Range:** < 0°F or > 110°F (< -18°C or > 43°C)

- System protection mode activated
- Automated shutdown procedures
- Data validity cannot be guaranteed

## 4.2 Precipitation Validity Ranges

### No Impact Range

**Precipitation:** 0-0.02 inches/hour

- Full system performance maintained
- All accuracy specifications met

## **Minimal Impact Range**

**Precipitation:** 0.02-0.1 inches/hour

- Camera performance: 95-98% of optimal
- Radar performance: 98-100% maintained
- Overall system degradation: < 5%

## **Moderate Impact Range**

**Precipitation:** 0.1-0.25 inches/hour

- Camera performance: 80-94% of optimal
- Radar performance: 90-97% maintained
- Overall system degradation: 10-20%

## **Severe Impact Range**

**Precipitation:** > 0.25 inches/hour

- Camera performance: < 80% of optimal
- System switches to radar-primary mode
- Manual verification recommended

## **4.3 Visibility Validity Ranges**

### **Excellent Conditions**

**Visibility:** > 10 miles

- Full optical performance
- Maximum detection range achieved

### **Good Conditions**

**Visibility:** 5-10 miles

- Minimal performance impact
- Detection range: 95-100% of maximum

### **Fair Conditions**

**Visibility:** 2-5 miles

- Moderate performance impact
- Detection range: 80-94% of maximum
- Increased false positive rate possible

### **Poor Conditions**

**Visibility:** 0.5-2 miles

- Significant performance degradation
- Detection range: 50-79% of maximum
- High false positive/negative rates

### **Severe Conditions**

**Visibility:** < 0.5 miles

- System reliability compromised
- Radar-only operation recommended
- Visual detection suspended

## **5. System Performance Validity Ranges**

### **5.1 Processing Latency Ranges**

#### **Real-Time Performance**

**Latency:** 50-100 milliseconds

- Live traffic monitoring capability
- Immediate alert generation possible
- Real-time dashboard updates

#### **Near Real-Time Performance**

**Latency:** 100-500 milliseconds

- Slight delay in live updates
- Acceptable for most applications
- No impact on data accuracy

#### **Delayed Processing**

**Latency:** 500-2000 milliseconds

- Noticeable delay in system response
- Batch processing recommended
- Real-time alerts may be unreliable

## **System Overload**

**Latency:** > 2000 milliseconds

- System performance severely impacted
- Frame dropping likely
- Data accuracy compromised

## **5.2 Data Storage Validity Ranges**

### **Optimal Storage Performance**

**Available Storage:** > 80% free space

- Full data retention capability
- All features operational
- No storage-related performance impact

### **Moderate Storage Usage**

**Available Storage:** 50-80% free space

- Automated data cleanup activated
- Older data archived or compressed
- Minor performance impact possible

### **High Storage Usage**

**Available Storage:** 20-50% free space

- Aggressive data management required
- Reduced data retention period
- Performance degradation likely

### **Critical Storage Level**

**Available Storage:** < 20% free space



- Emergency data purging activated
- System stability at risk
- Immediate intervention required

## 6. Statistical Validity and Confidence Intervals

### 6.1 Sample Size Requirements for Valid Statistics

#### Hourly Statistics

**Minimum Sample:**  $n \geq 30$  vehicles **Confidence Level:** 90% **Margin of Error:**  $\pm 5\%$  for proportions

#### Daily Statistics

**Minimum Sample:**  $n \geq 100$  vehicles **Confidence Level:** 95% **Margin of Error:**  $\pm 3\%$  for proportions

#### Weekly/Monthly Statistics

**Minimum Sample:**  $n \geq 500$  vehicles **Confidence Level:** 99% **Margin of Error:**  $\pm 2\%$  for proportions

### 6.2 Measurement Uncertainty Ranges

#### Speed Measurements

- **Standard Uncertainty:**  $u = 1.2$  mph ( $k=1$ )
- **Expanded Uncertainty:**  $U = 2.4$  mph ( $k=2$ , 95% confidence)
- **Calibration Uncertainty:**  $\pm 0.5$  mph (reference standard)

#### Count Measurements

- **Detection Rate Uncertainty:**  $\pm 2.5\%$  (95% confidence)
- **Classification Uncertainty:**  $\pm 5\%$  per vehicle class
- **Temporal Accuracy:**  $\pm 0.1$  seconds for timestamps

## 7. Boundary Conditions and Failure Thresholds

### 7.1 System Shutdown Triggers

- CPU temperature  $> 85^{\circ}\text{C}$
- Available RAM  $< 10\%$
- Storage space  $< 5\%$
- Power supply voltage deviation  $> \pm 15\%$

- Network connectivity lost > 24 hours (for cloud-dependent features)

## 7.2 Data Quality Flags

- **High Quality:** All sensors operational, optimal conditions
- **Good Quality:** Minor degradation, 95%+ performance maintained
- **Fair Quality:** Moderate degradation, 80-94% performance
- **Poor Quality:** Significant degradation, 60-79% performance
- **Invalid:** Performance < 60% or sensor malfunction

## 7.3 Validation Frequency Requirements

- **Real-time validation:** Continuous during operation
- **Daily validation:** Automated self-tests and calibration checks
- **Weekly validation:** Performance statistics review
- **Monthly validation:** Full system calibration against reference standards
- **Annual validation:** Comprehensive accuracy assessment and recertification

This quantitative framework provides clear operational boundaries and performance expectations for all system outcomes, enabling objective assessment of data validity and system reliability under varying conditions.