

Safety Assessment of UAV Operations in U-Space: A Comprehensive Study on Key Safety Metrics

Version 1.0

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Abstract

In this technical report, we introduce two categories of safety metrics including collision metrics and surveillance performance metrics. We also identify and classify influencing factors into three main categories consists of technical, environmental, and operational factors. We then analyze the impact of these factors on the defined metrics within the context of U-space.

1. Introductions

Unmanned Aerial Vehicles (UAVs), or drones, are increasingly used across various sectors and are expected to grow rapidly in civilian airspace in the coming years. In this context, effective traffic management becomes essential. UTM (Unmanned Traffic Management) and U-space are regulatory frameworks designed to manage drone traffic by providing various services. In U-space several strategic phase services (i.e., pre-flight) such as strategic conflict detection, strategic conflict resolution, and tactical phase services (i.e., in-flight) such as tactical conflict detection, and tracking are available to enhance the safety in this crowded and complex airspace.

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Despite the availability of U-space services, defining reliable metrics to quantitatively assess operational safety and ensure the Target Level of Safety (TLS) under both normal and abnormal conditions remains a major challenge. This technical report presents an analysis of how abnormal conditions—such as GPS faults, IMU (Inertial Measurement Unit) faults, wind, and combinations of sensor faults with wind—affect These metrics.

These results can be useful for monitoring system to find the metrics which are more sensitive to the safety risk and analyzing the impact of the different factors on metrics to find which factor can have more impact on which metrics and finding the good metrics which are the metrics that are more sensitive to the risk of collision between drones.

2. Safety Factors

We categorized the safety metrics into three different factors including technical factors, environmental factors, and operational factors.

- Technical Factors: These involve system-related issues, where technical malfunctions or external intrusions in UAV components can lead to faults or failures, affecting overall operational safety. In this technical report we considered GPS Faults and IMU Faults as technical factors.
- Environmental Factors: These factors refer to the natural conditions that can affect UAV operations, such as wind.
- Operational Factors: These factors directly influence the safety of UAV operations based on both the operational environment and the performance of the UAVs. They include aspects such as different UAV speeds, different Update Intervals (UIs), and different air traffic density (high, medium, or low). We considered different levels of air traffic based on three features: (1) the distance between the target UAV and adjacent UAVs on its left and right sides: 10 meters for high traffic, 100 meters for medium traffic, and 200 meters for low traffic; (2) the number of traffic layers: three layers with 10 meter spacing for high traffic, two layers with 100 meter spacing for medium traffic, and one layer with 200 meter spacing for low traffic; and (3) the flow rate, defined as a 0.4 second interval between consecutive flights, representing a worst-case scenario in which a drone is nearly always present at a fixed distance on both sides of the target UAV. These values for low, medium, and high traffic levels were defined based on extensive experimentation carried out both in this study and in our previous work.

3. Safety metrics

In this technical report, we classified the safety metrics into two different categories including the collision metrics and surveillance performance metrics.

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- **Collision metrics:**

we considered collision metrics as quantitative measures used to assess the frequency, likelihood, severity, and potential consequences of collisions or conflicts between drones. The following introduces these metrics.

- **Number of Collisions:** The total number of UAV collisions along a flight path. A collision is defined when the distance between two drones becomes less than the sum of their motor-to-motor dimensions and propeller diameters.
- **Number of Conflicts:** The Number of Conflicts metric counts instances where the safety zones, or "separation bubbles," of two UAVs overlap.
- **Frequency of Collision:** Frequency of collision is calculated as all the collisions caused in the flight duration, divided by the sum of the flight time of each of the UAV involved, as shown in the Eq 1, where T_i is the total time flown by the number of drones n.

$$F_{Collisions} = \frac{N_{Collisions}}{\sum_{i=1}^n T_i}$$

- **Frequency of Conflict:** Frequency of conflict is calculated as all the conflicts caused in the flight duration, divided by the sum of the flight time of each of the UAV involved, as shown in the Eq 2, where T_i is the total time flown by the number of drones n.

$$F_{Conflicts} = \frac{N_{Conflicts}}{\sum_{i=1}^n T_i}$$

- **Incomplete missions' percentage (IMP):** This metric indicates the percentage of missions that were not successfully completed due to collisions, crashes, or the activation of fail-safe mechanisms, out of all faulty missions executed.
- **Number of Inner Separation Minima Violations (ISMV):** The inner bubble size is calculated using a fixed formula, as shown in Equation 3, with all measurements standardized in meters for consistency. In this equation, D_o represents the drone's total dimensions, including wingspan, while D_s denotes the manufacturer's recommended safety distance. D_m denotes the maximum distance a drone can travel at peak speed between tracking intervals, remains constant for a mission but may vary by drone model and mission.

$$\text{Bubble}_{\text{inner}} = D_o + \max(D_s, D_m)$$

- **Number of Outer Separation Minima Violations (OSMV):** The outer separation minima assign a protective bubble around each drone, influenced by factors like weight, speed, navigation, and communication with UTM/U-space, following U-space guidelines [?]. There is currently no standardized method for calculating these minima in urban airspace, emphasizing the need to define them for this study. Equation 4, calculates the dynamic bubble using current and previous airspeeds, $S_a(t_n)$ and $S_a(t_n-1)$ and the last distance covered by drone $D(t_n-1)$ represents the last distance covered by the drone, these parameters are used to compute the anticipated distance to be covered at time t_n :

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$$D(t_n) = D(t_{n-1}) \times \frac{Sa(t_n)}{Sa(t_{n-1})}$$

The relative change in anticipated distance, based on airspeed variations (as in Equation 4), determines the extra space required beyond the drone's minimum inner bubble radius. Finally, as shown in Equation 5, The radius of the outer bubble is computed by multiplying the inner bubble radius by the calculated distance and a risk factor R (e.g., for simplicity in this study, R is set to 1), which accounts for factors like airspace density, weather, and U-space performance.

$$Bubble_{outer}(t) = R \times (Bubble_{inner} \times \max(1, D(t_n)))$$

▪ Surveillance Performance Metric

Measuring surveillance performance is vital for ensuring Target Level of Safety (TLS) in UAV operations, as it maintains separation and verifies telemetry data (Target Reports, TRs). To be effective in UTM systems or U-Space, telemetry must meet standards for completeness, precision, update rate, latency, and integrity. Surveillance performance is evaluated by classifying target reports based on their positional accuracy relative to a reference path, a necessary step before metric calculation. These reports are categorized into specific classes, as shown in figure 1 and explained below.

- **Number of True Target Report (NTTR):** As shown in figure 1, TTR is a report received within the predefined bubble based on the drone's specifications, airspace density, and population type. It aligns with the reference path at the time the telemetry is received. A TTR occurs when the measured position is within a certain threshold distance from the reference trajectory at the same time.
- **Number of False Target Report (NFTR):** As show in 1, a FTR occurs when the distance between a UAV's actual position and its position on the reference trajectory exceeds a specified threshold.
- **Number of Ghost Target Report (NGTR):** A GTR occurs when an extra report is received within a given update interval (UI), beyond the expected number. For example, if two target reports are expected within a UI but a third report is received, that extra report is classified as a ghost target report.

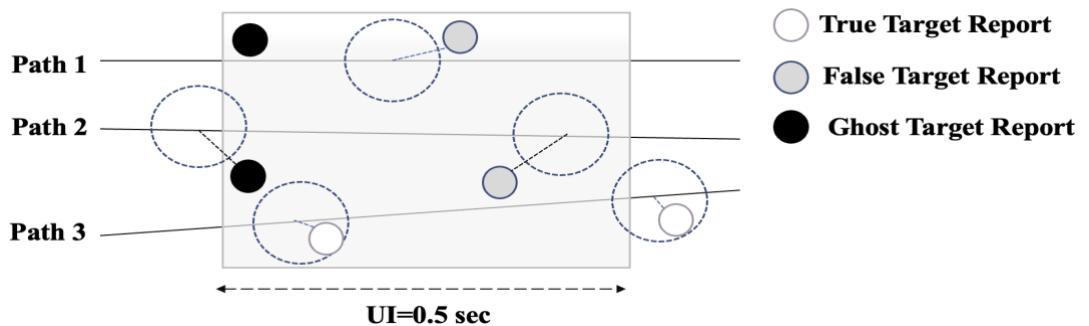


Figure 1 Visualization of Different Types of Target Reports.

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- **Probability of Update (PU):** This metric quantifies the probability that a True Target Report (TTR) aligns with the reference trajectory during a specified Update Interval (UI) by calculating the proportion of time the UAS is tracked relative to its expected trajectory. Data loss, denoted by G, occurs when the time between two target reports meets or exceeds the UI, which calculates as follow, where UI is the Update Interval and N is the number of intervals.

$$\text{Total Loss Period} = \sum_{t=1}^N L_t \quad L_t > 0,$$

where $L_t = G_t - UI$

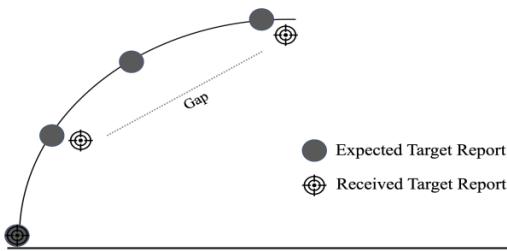
$$PU = 1 - \frac{\text{Total Loss Period}}{\text{Total Flight Duration}}$$

The Probability of Update, measures how consistently the UAV is tracked relative to its expected trajectory.

- **Probability of Long Gap (PLG):** As shown in Figure 2, this metric measures the probability of missing a True Target Report over consecutive Update Intervals (UIs). It is calculated based on the total loss periods, as defined below:

$$\text{Total Gap Period} = \sum_{t=1}^N G_t \quad G_t > 2 * UI$$

$$PLG = \frac{\text{Total Gap Period}}{\text{Total Flight Duration}}$$

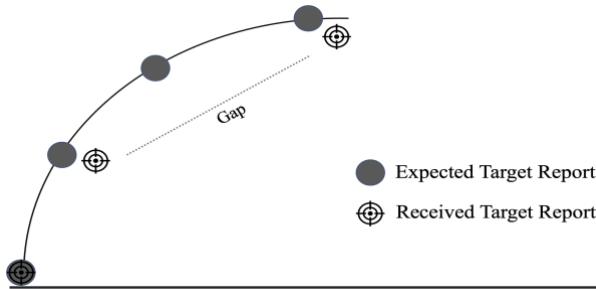


- **Horizontal and Vertical Position Accuracy (HPA, VPA):** Surveillance systems with higher accuracy metrics, measured by the root mean square (RMS) of position errors in horizontal (HPA) and vertical (VPA) dimensions, improve the smoothness of data for traffic management in high-density airspace. Lower precision can necessitate adjustments to separation minima and flight plans. These accuracy metrics quantify the difference between received and expected target reports, Where erh_i^2 and erv_i^2 are the position errors in absolute value and N is the total number of true targets considered for the metric.

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$$HPA_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N erh_i^2}$$

$$VPA_{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^N erv_i^2}$$



- **Density of False and Ghost Target Report (DFTR, DGTR):** The Density of False Target Reports DFTR is calculated as the ratio between the number of false targets and total number of target reports considered as can be seen in bellow:

$$DFTR = \frac{\text{Total Target Reports}_{False}}{\text{Total Target Reports}}$$

Similarly, the Density of Ghost Target Reports DGT R is calculated as the ratio between the number of ghost targets and total number of target reports considered as can be seen in bellow:

$$DGTR = \frac{\text{Total Target Reports}_{Ghost}}{\text{Total Target Reports}}$$

- **Probability of False or Ghost Track (PFT, PGT) :** The probability of false track is defined by dividing the total number of false UIs by the total number of UIs. A false UI is defined as an update interval in which at least one false target report is present alongside the true target report within it

$$\text{Probability of False Track} = \frac{\text{Number Of UI}_{False}}{\text{Total Number of UI}}$$

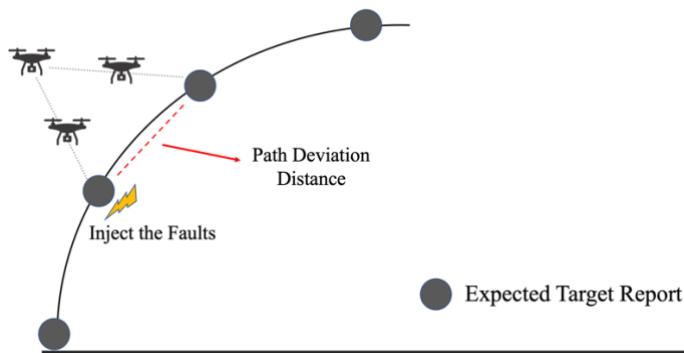
- the probability of Ghost Track is calculated by dividing the total number of ghost UIs by the total number of UIs. A ghost UI is defined as an update interval during which at least one ghost target report is present.

$$\text{Probability Of Ghost Track} = \frac{\text{Number Of UI}_{Ghost}}{\text{Total Number of UI}}$$

- **Flight Duration:** Flight Duration is a critical metric for operational efficiency and safety in UTM/U-space systems, as it directly impacts mission success in time-sensitive scenarios, measured from take-off to successful landing, or to the crash time if the drone failed.

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- **Distance to be Traveled:** This metric represents the total distance, measured in meters, that a drone is expected to travel under both faulty Run or gold Run conditions. It helps assess the drone's performance in completing its flight path, accounting for any deviations or anomalies.
- **Battery Consumption:** This metric calculates the percentage of battery consumed during a flight, based on the Iris drone model's 15-minute capacity, offering insights into energy efficiency by comparing battery usage with flight duration, mission requirements, and operational conditions.
- **Path Deviation Distance (Dist. Dev (m)):** In this metric as shown in Figure 4, the distance between when a drone deviates from its intended path and when it returns to it is considered.



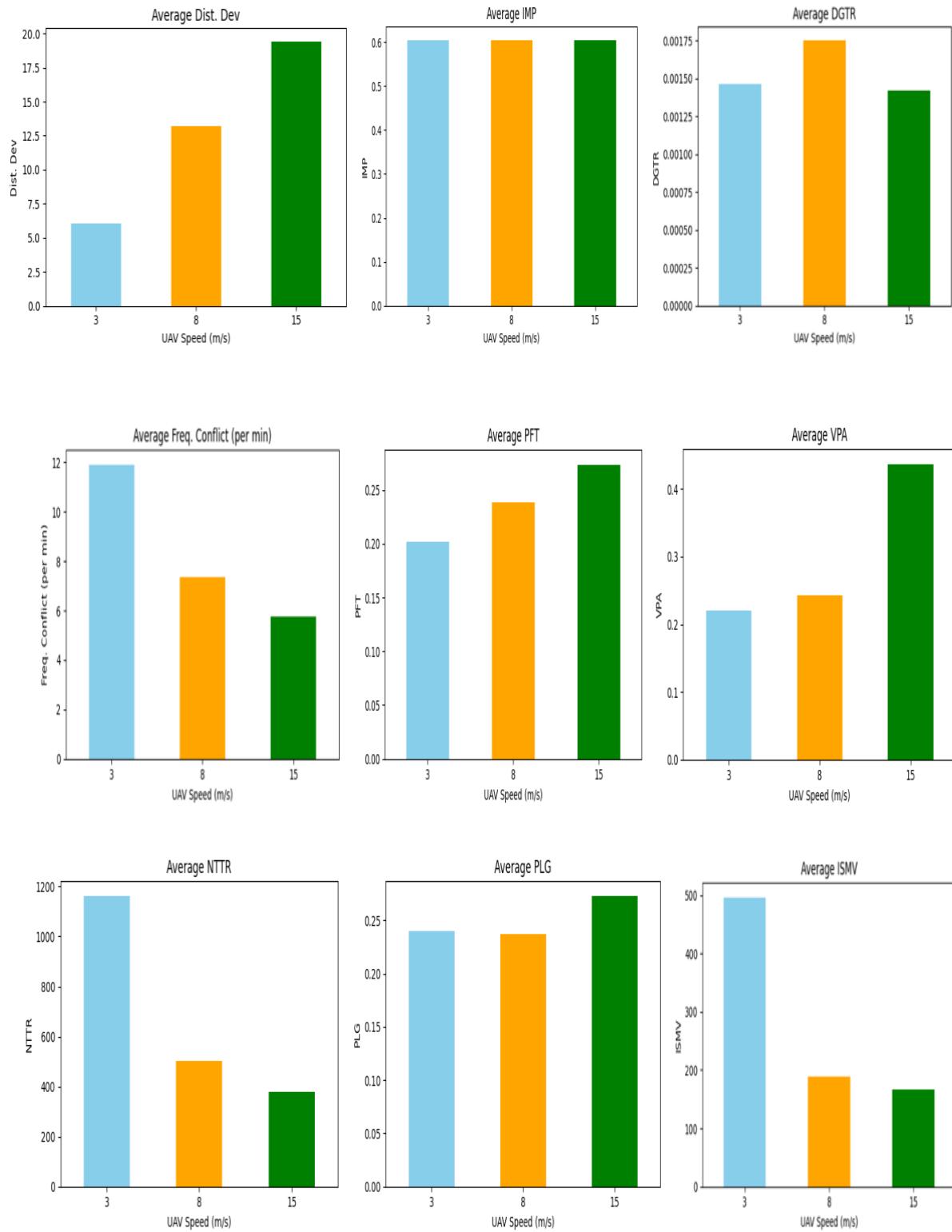
Results:

Impact of the different factors on GPS:

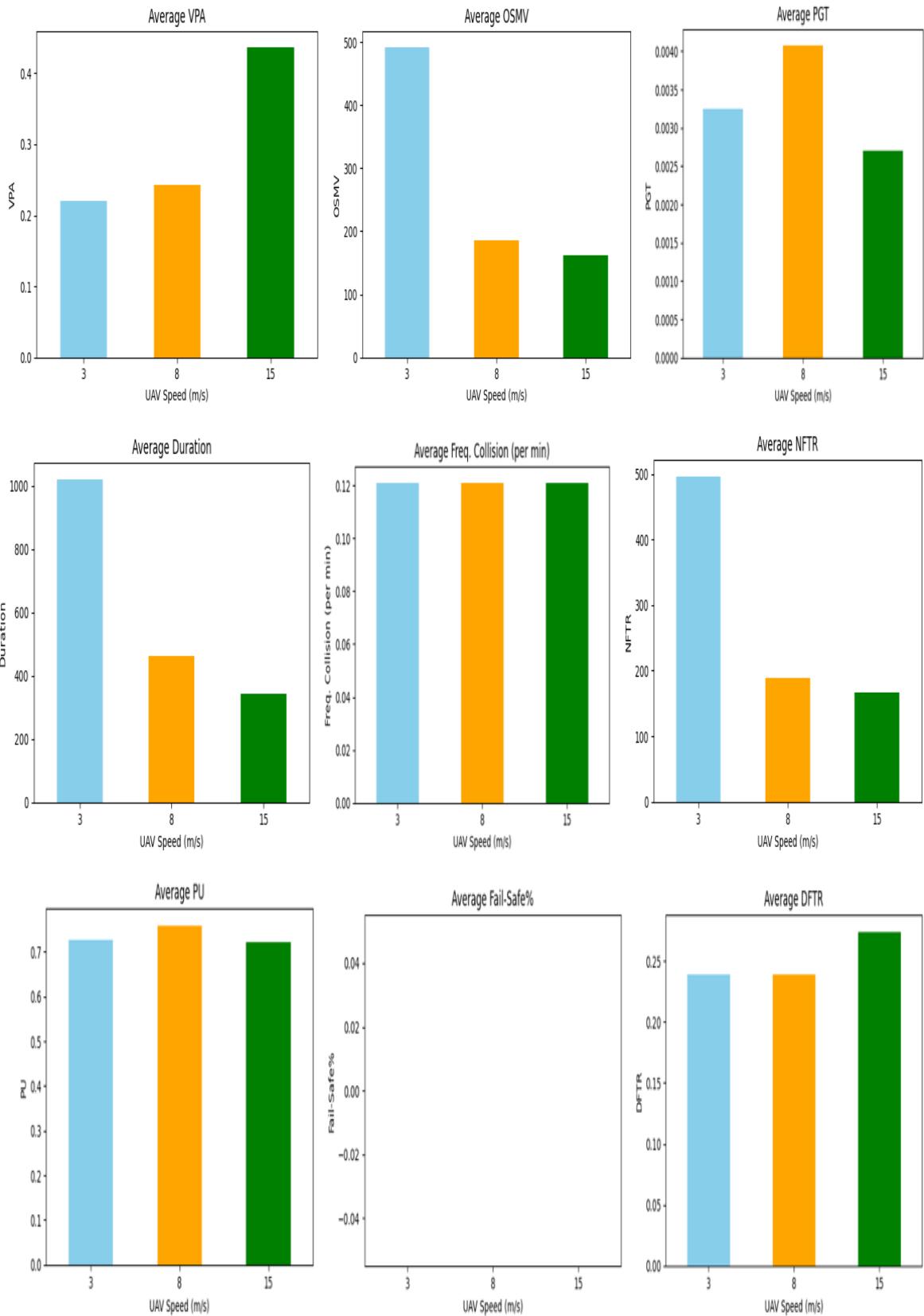
We injected three high-impact faults into the GPS module including Maximum Longitude, Maximum Latitude, and Random Value and analyzed their effects on various safety metrics. Following the fault injection, we further examined how different operational factors, including UAV speeds, update intervals (UIs), traffic levels, and injection durations, as well as an environmental factor (wind), influenced these metrics.

1) GPS Faults in light breeze wind

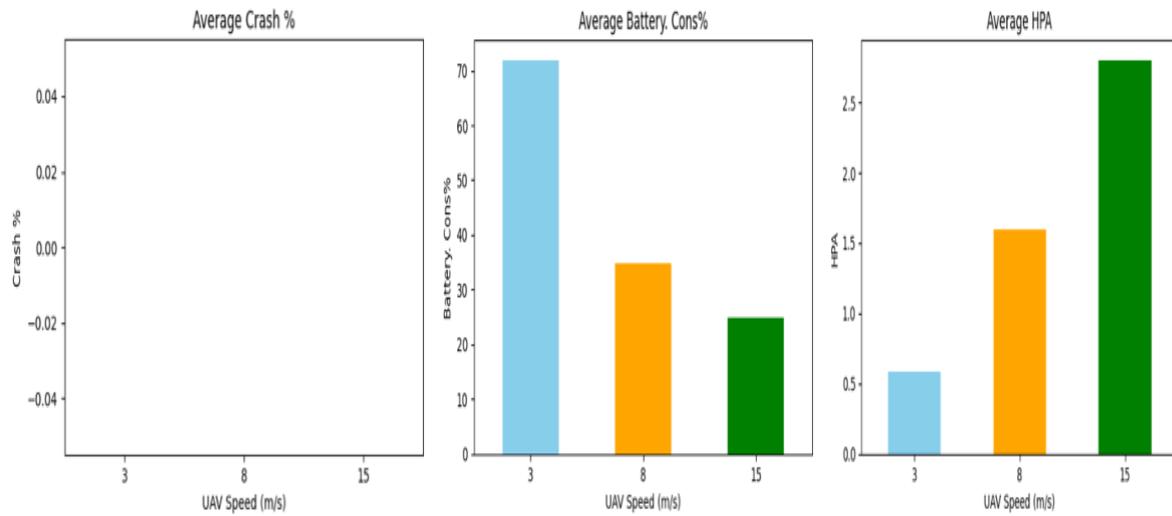
- Impact of the different UAV Speeds:



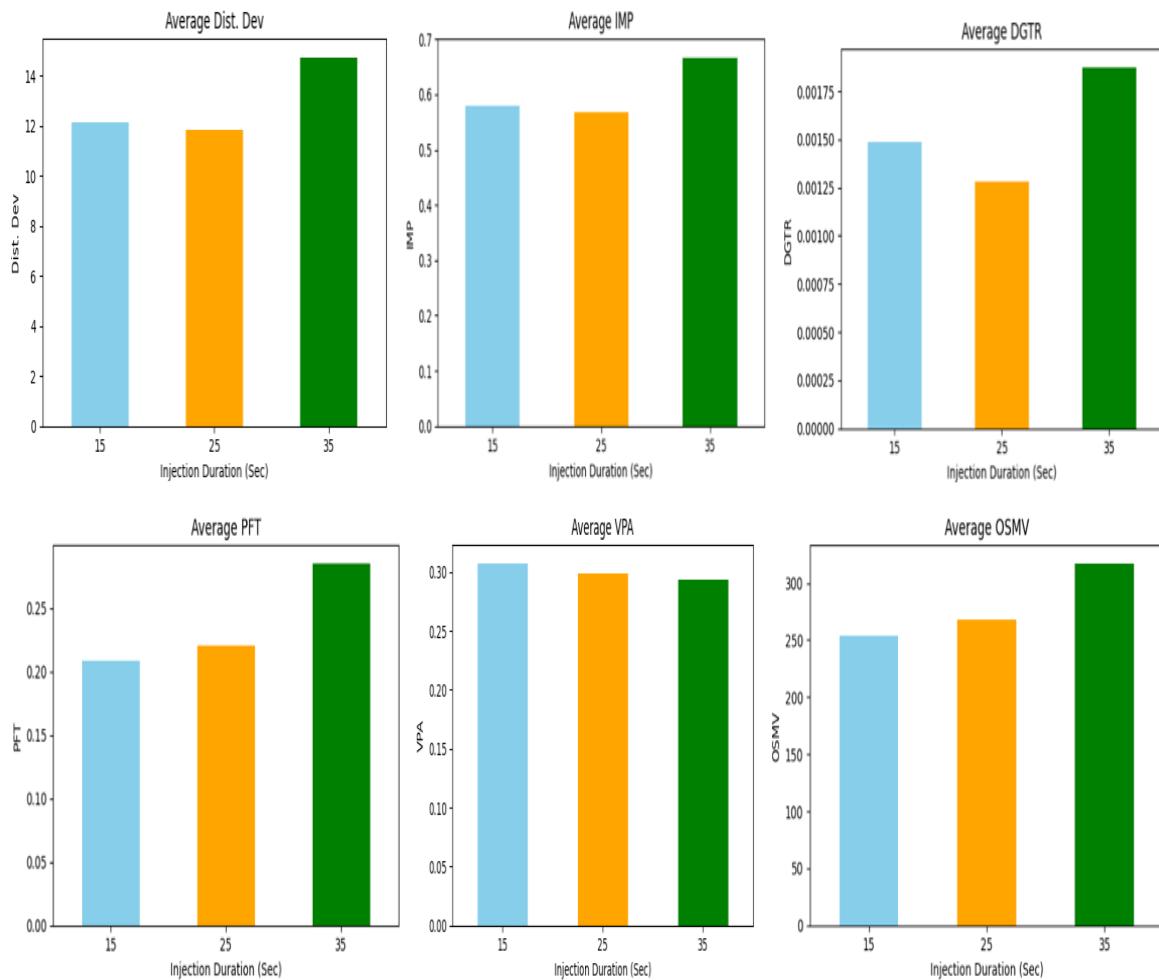
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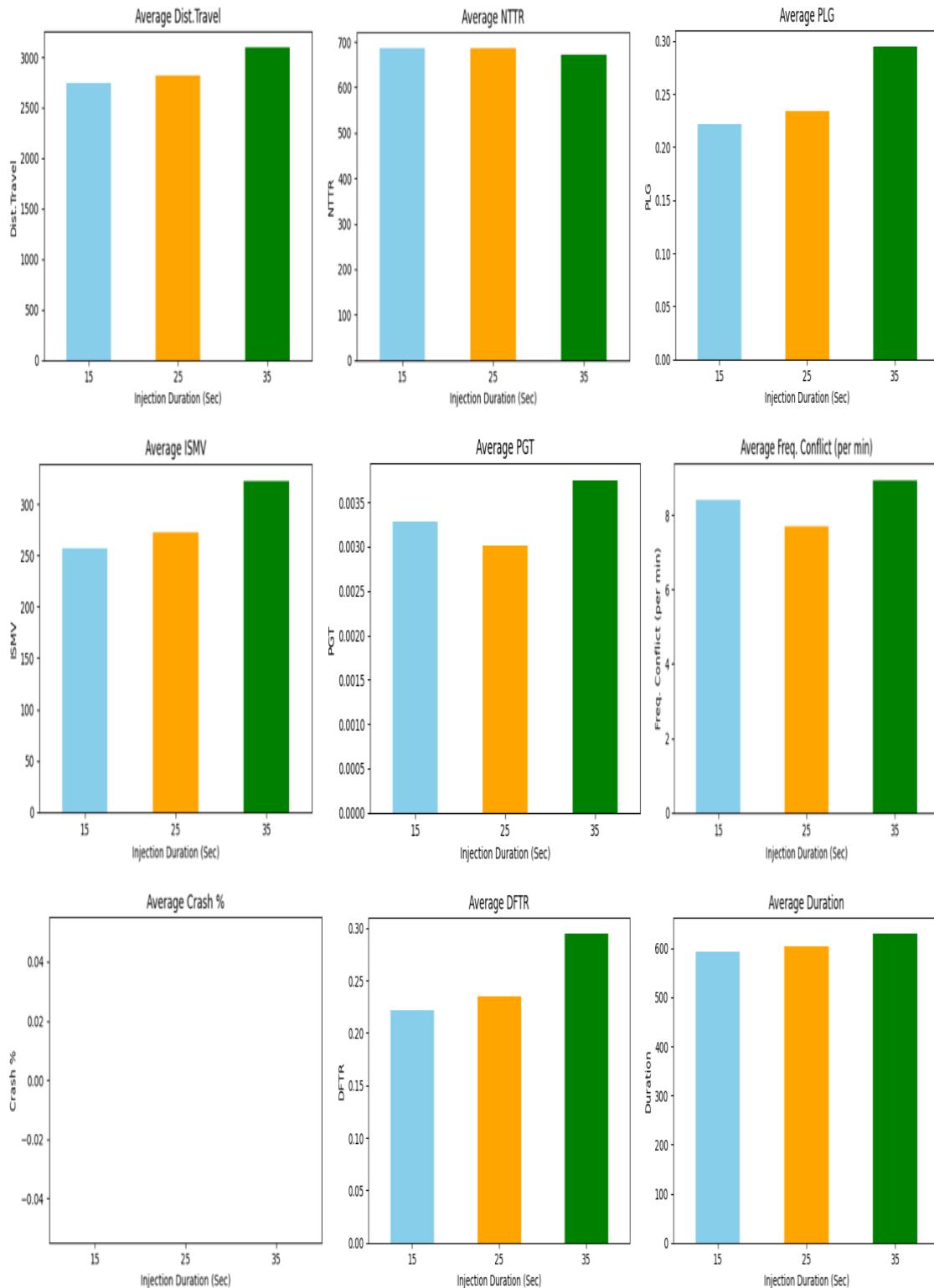
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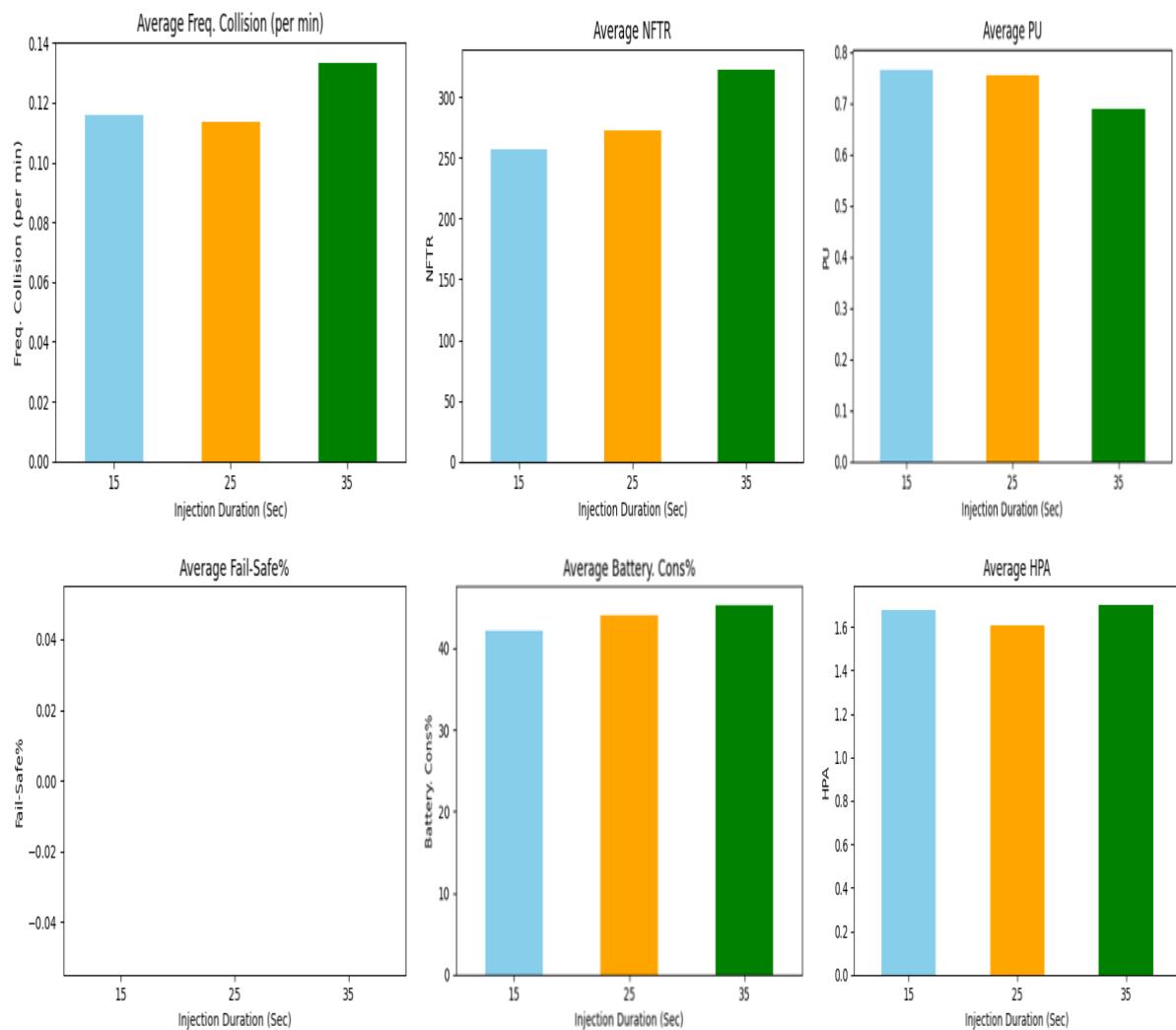
▪ Impact of the different injection duration:



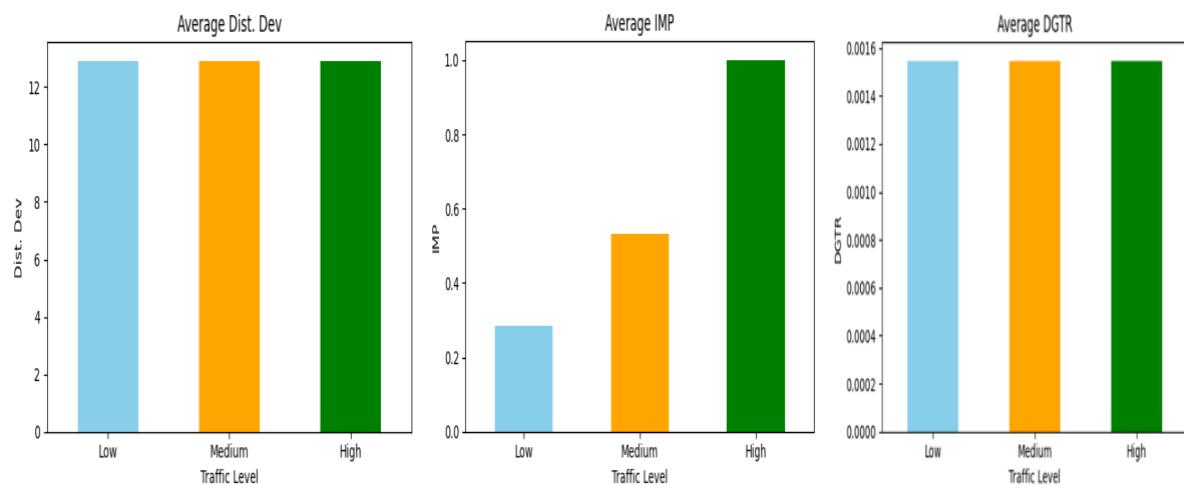
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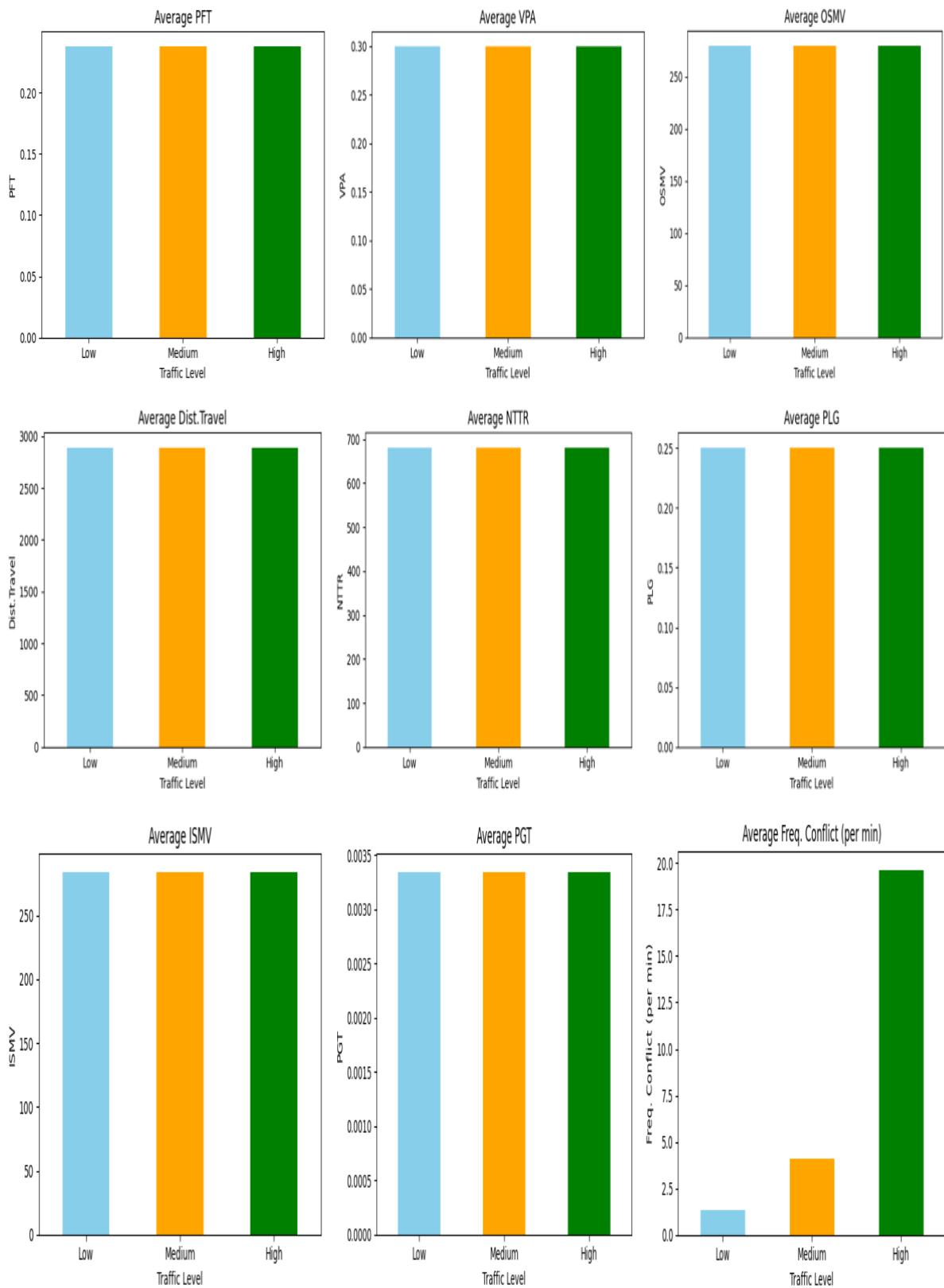
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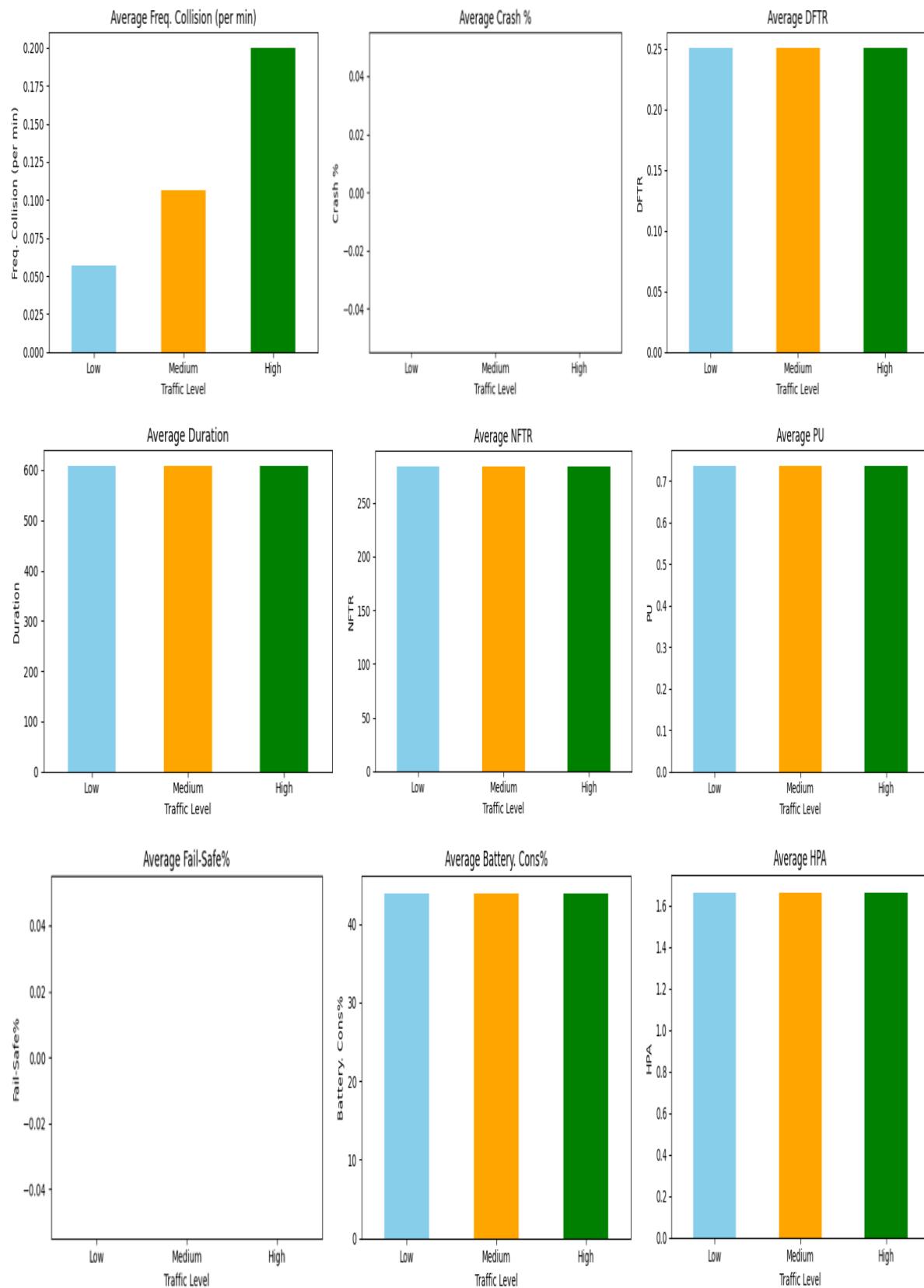
- **Impact of different Traffic Levels:**



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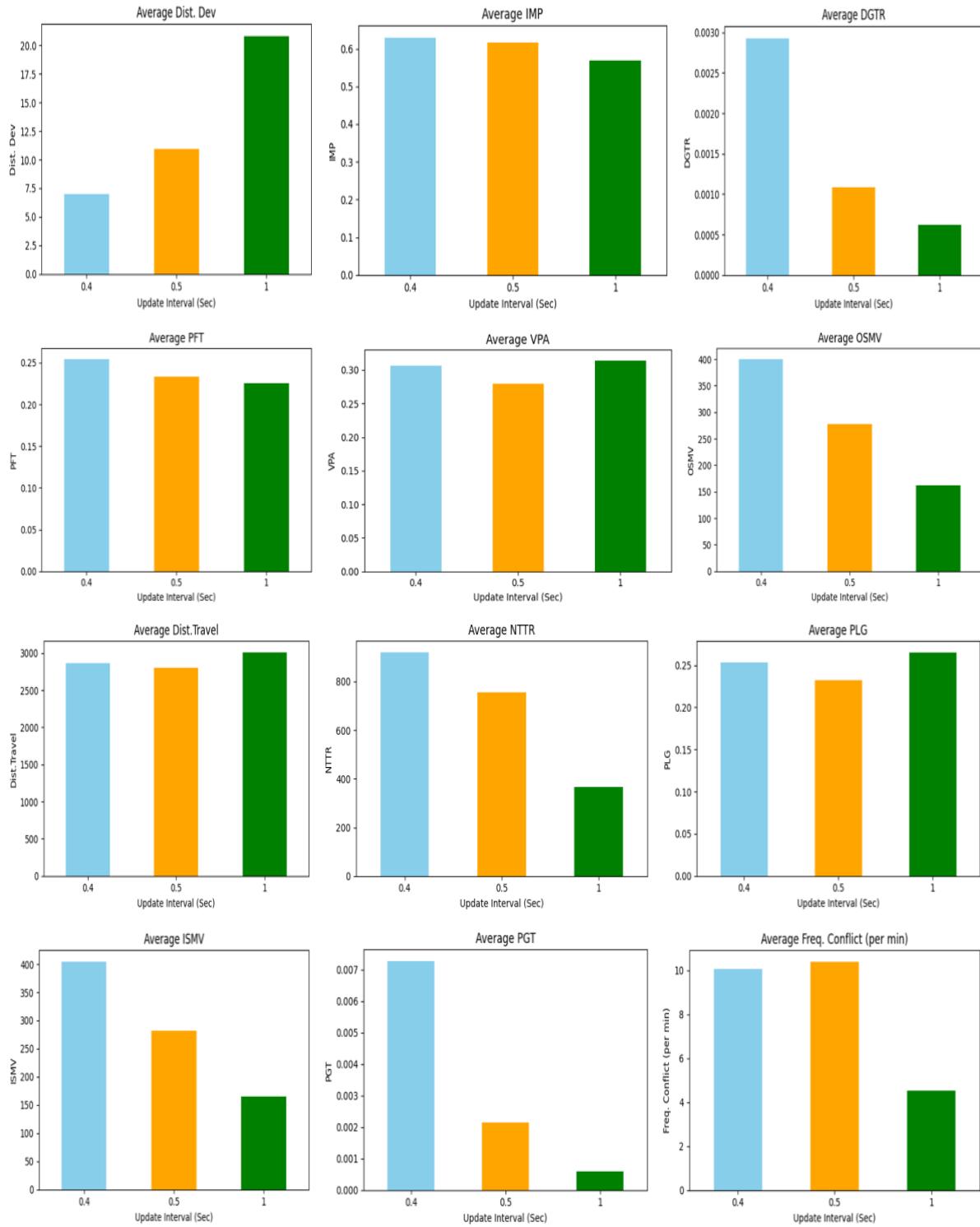


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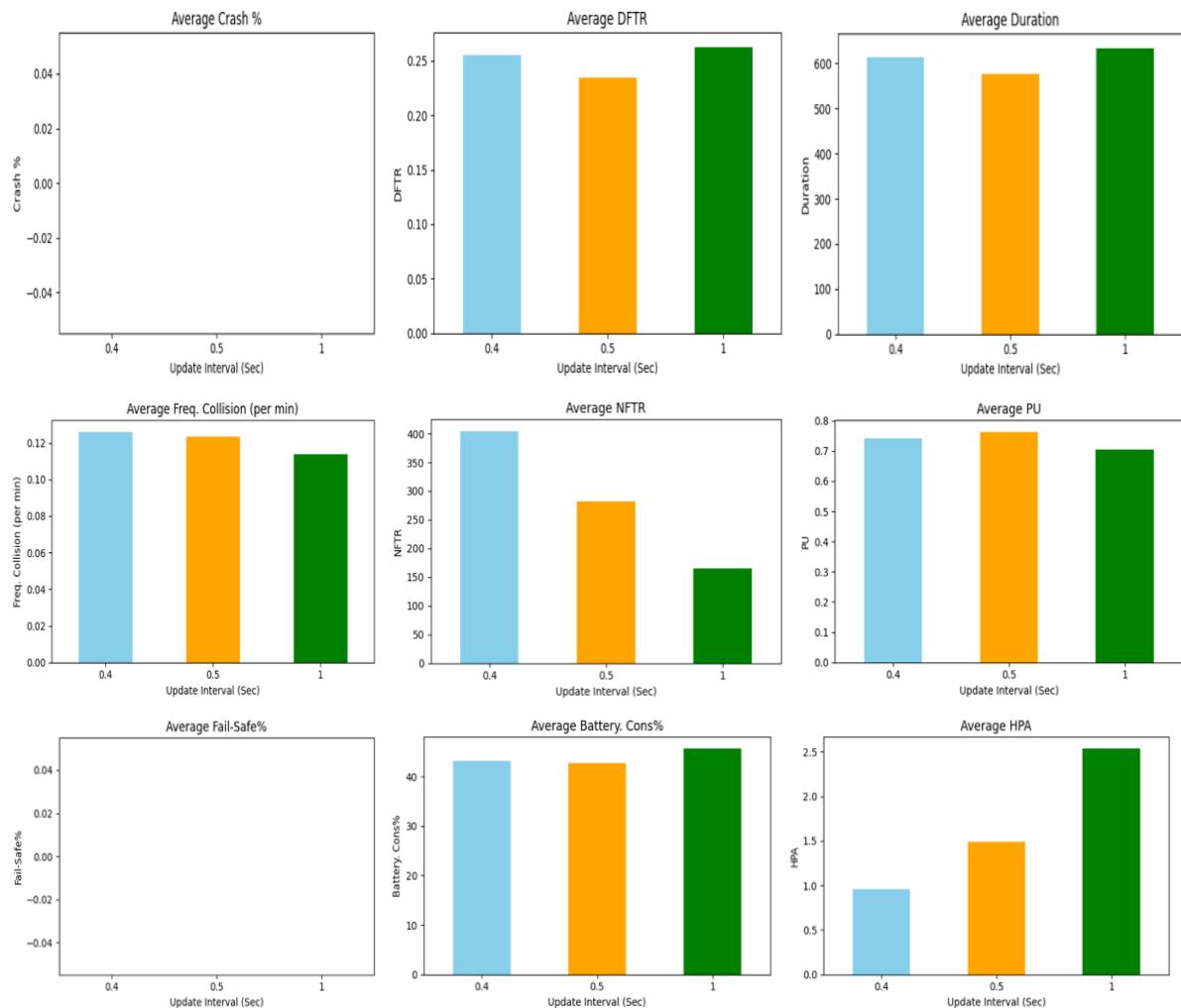


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- **Impact of different update interval:**

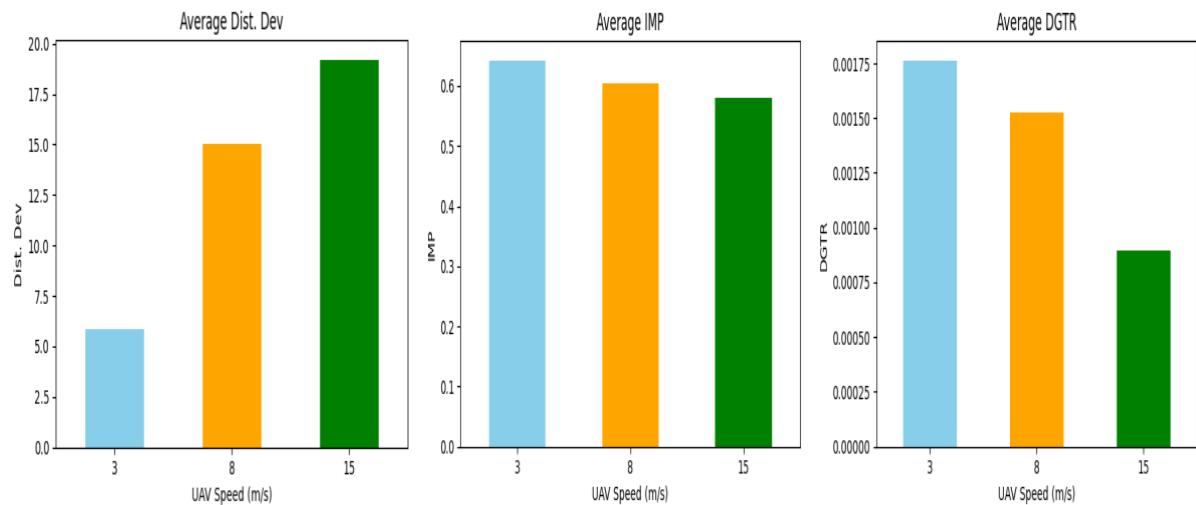


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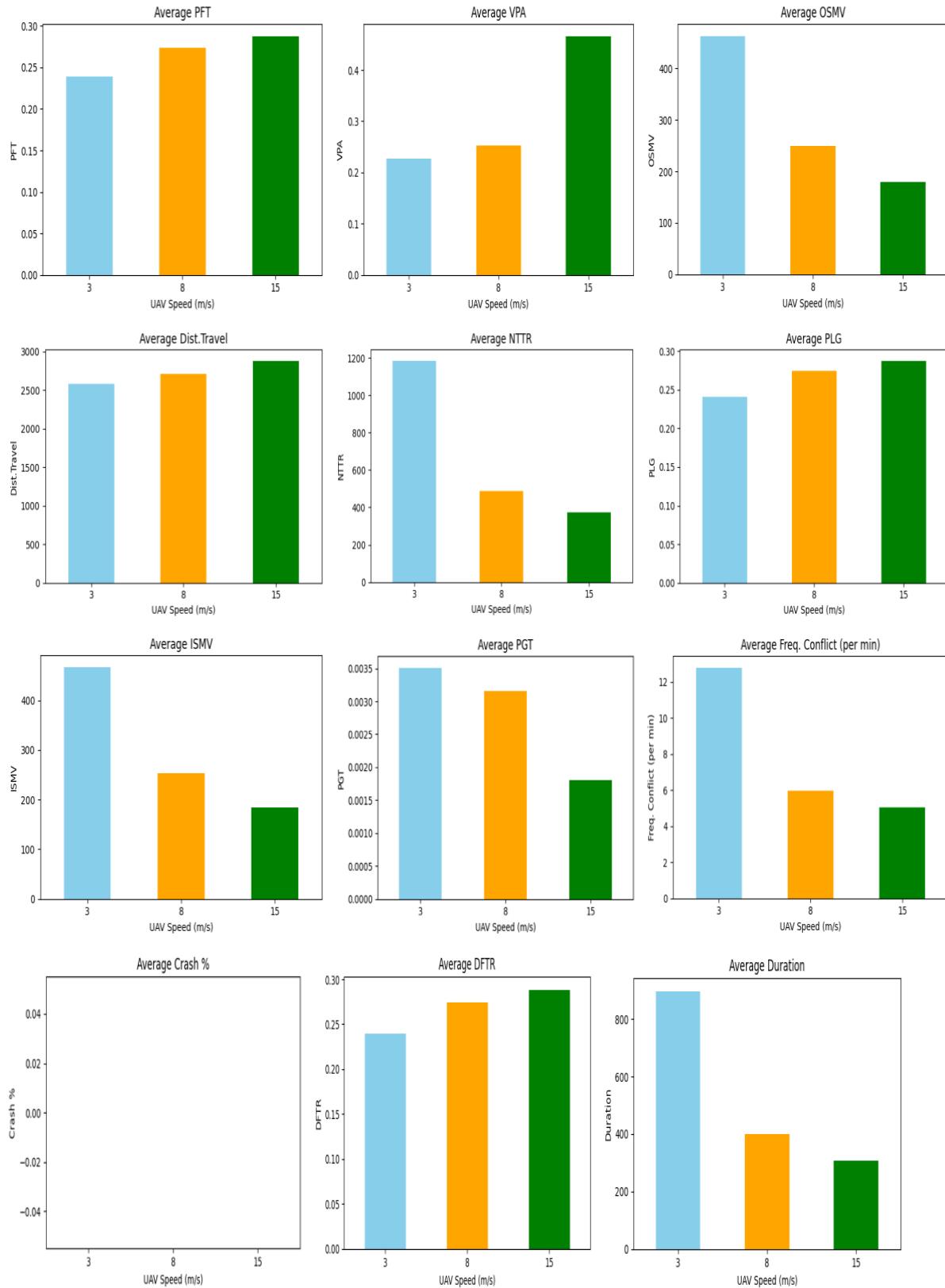


2) GPS Faults with moderate breeze:

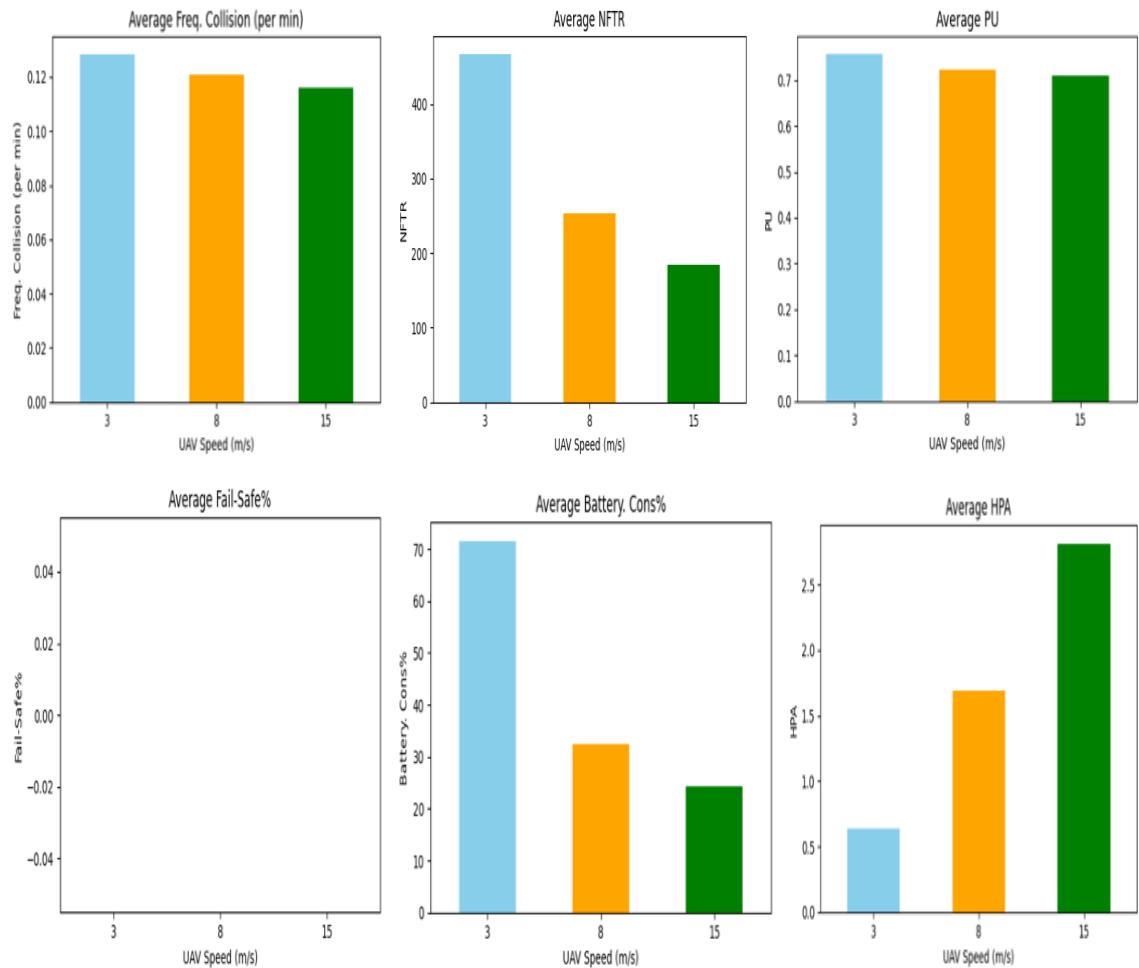
- Impact of the different UAV speeds:



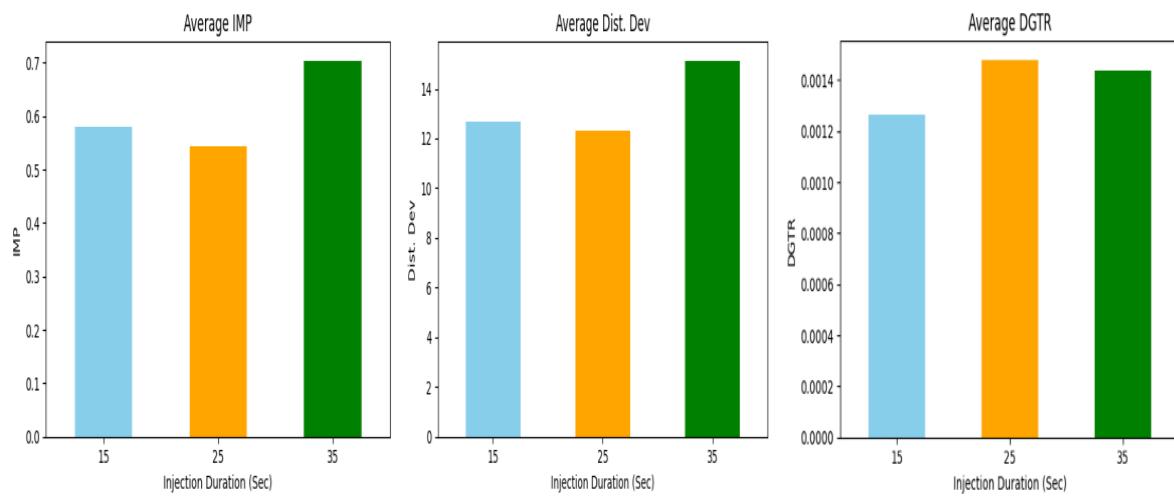
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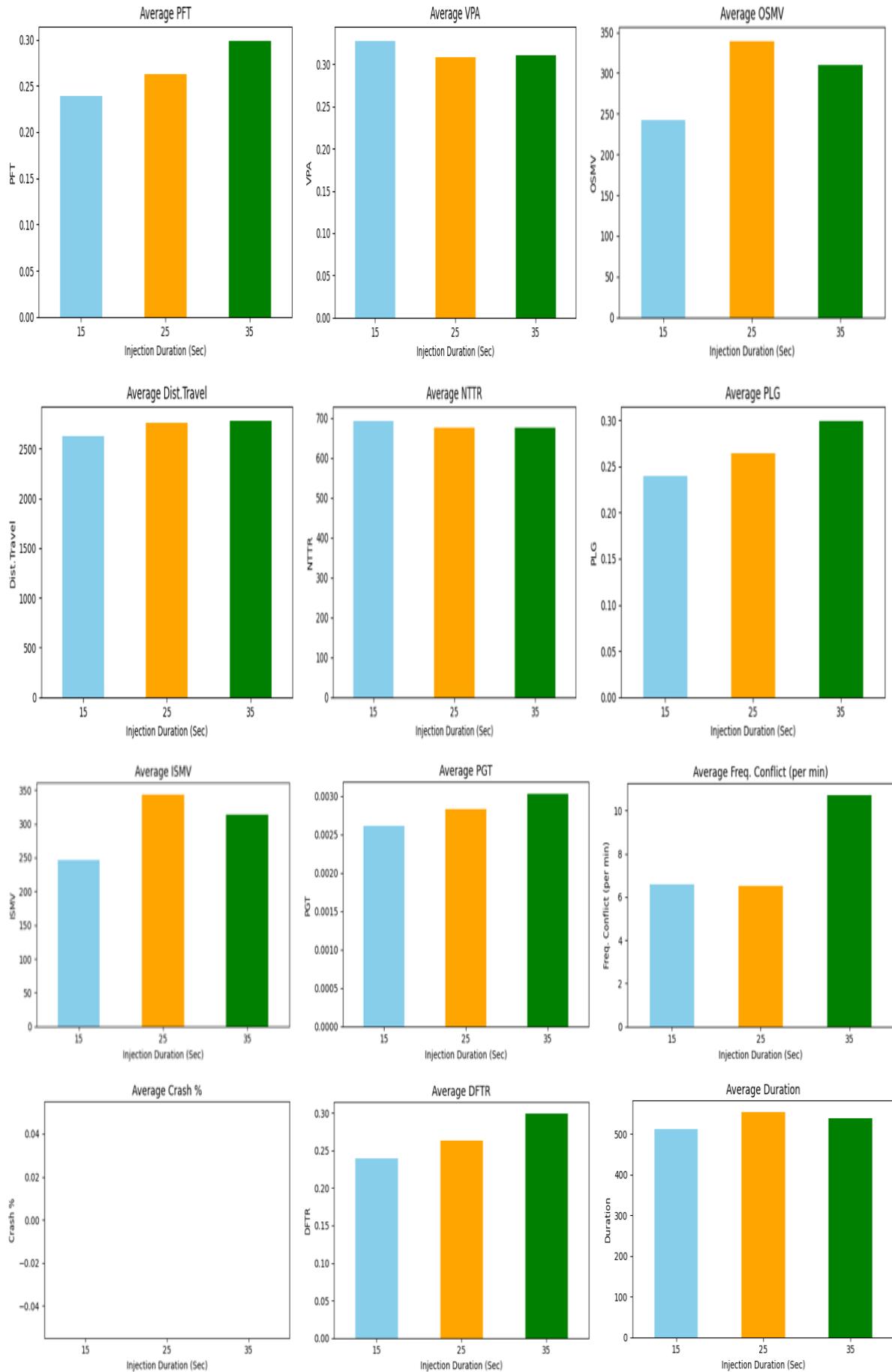
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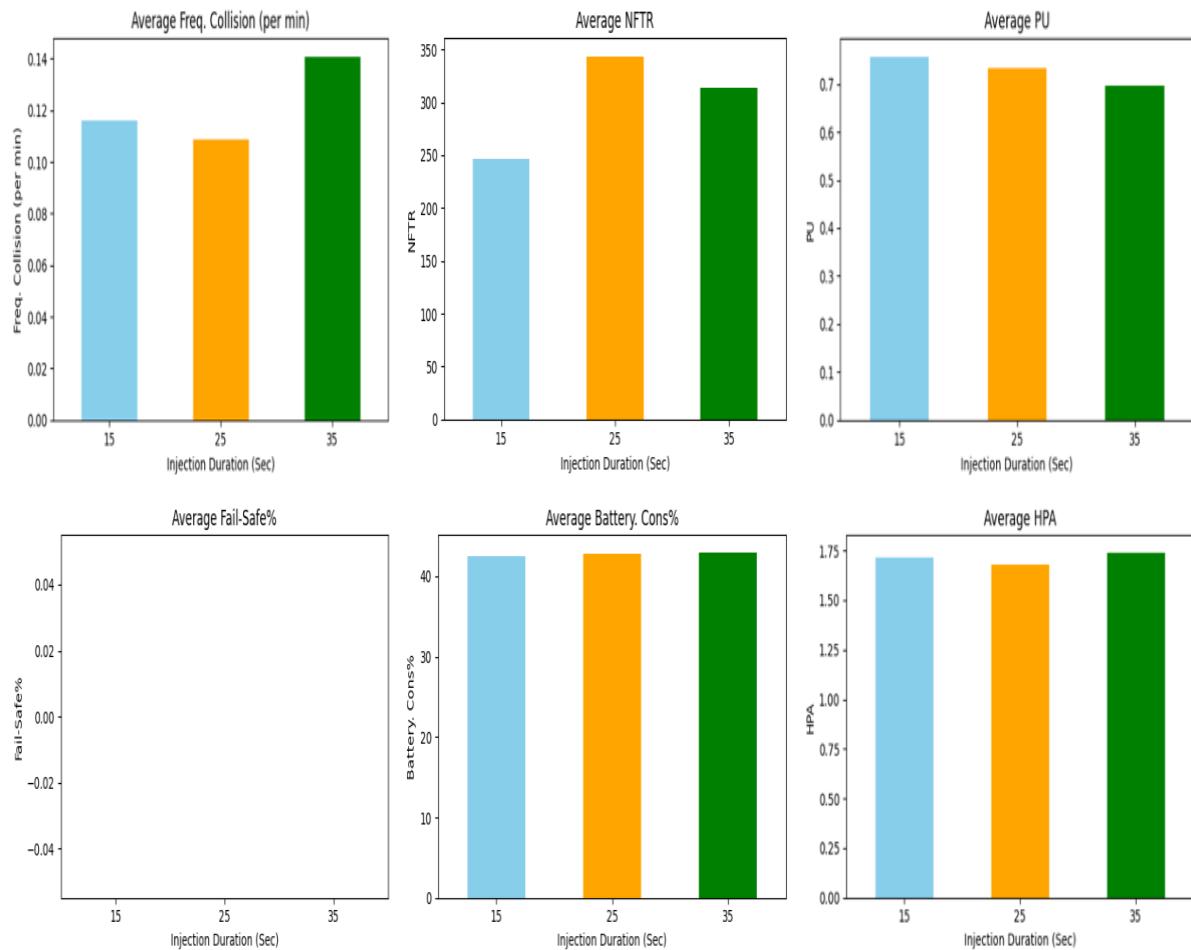
- **Impact of different injection durations:**



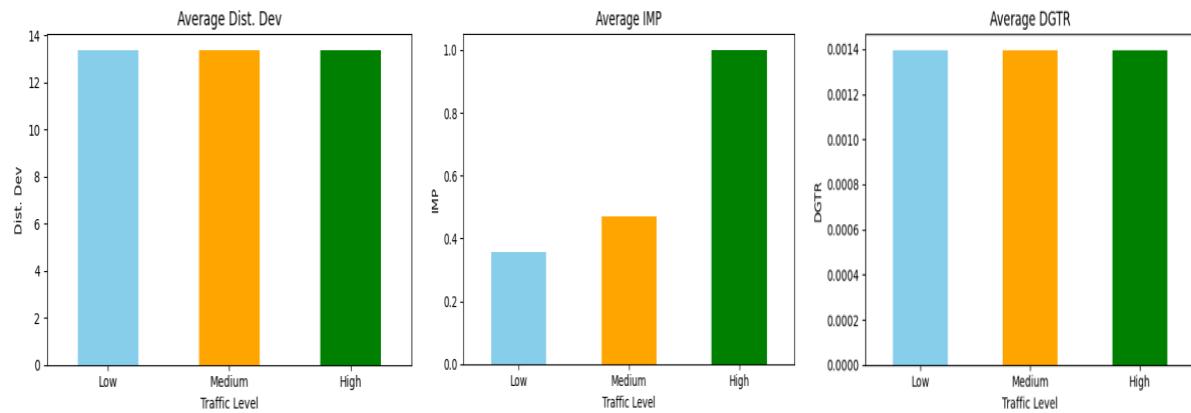
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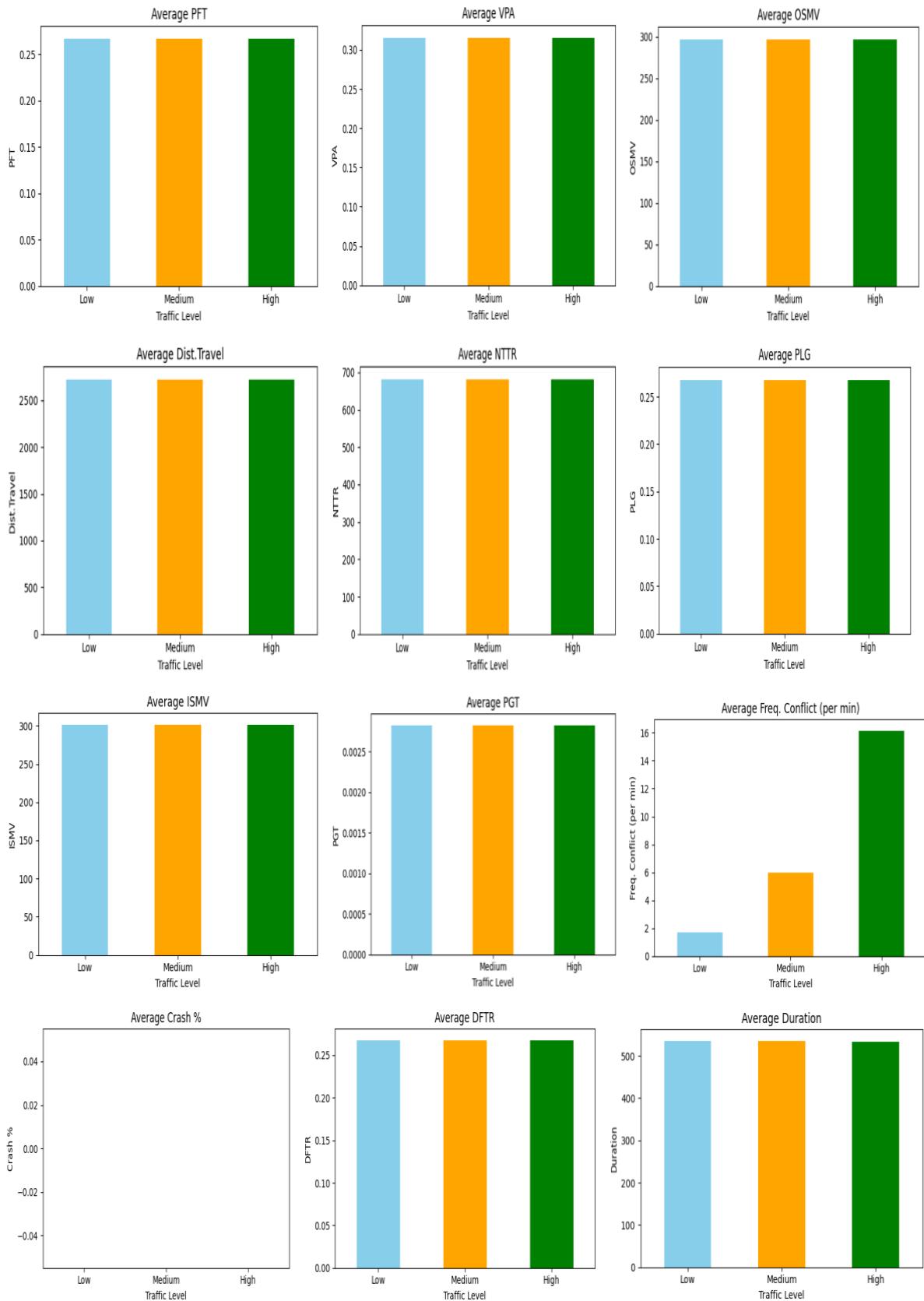
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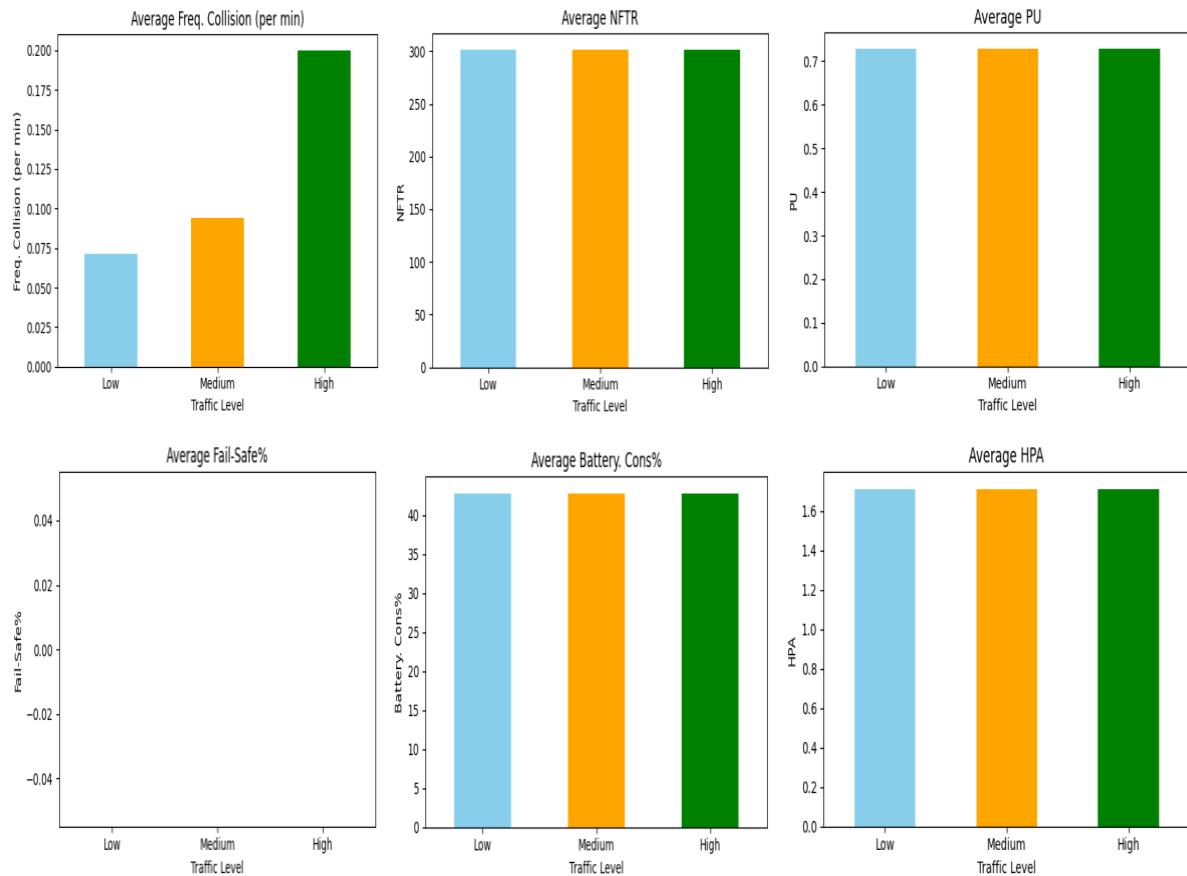
- Impact of the different traffic levels:



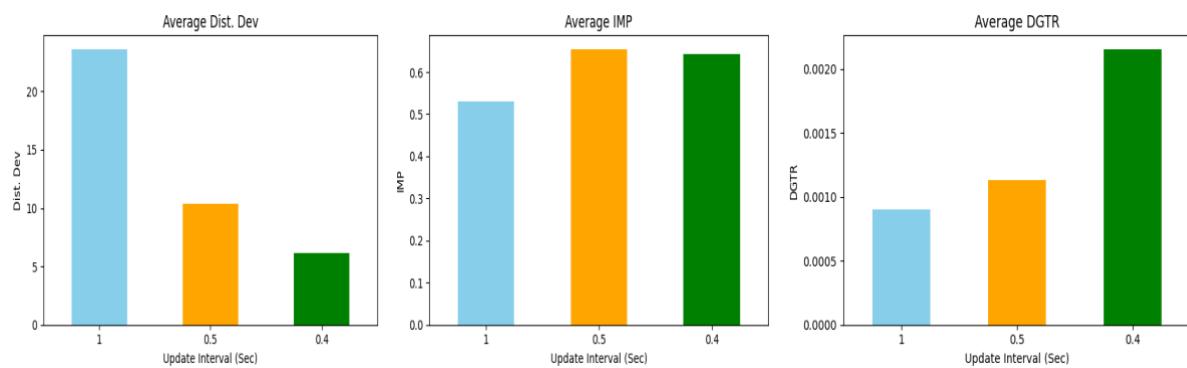
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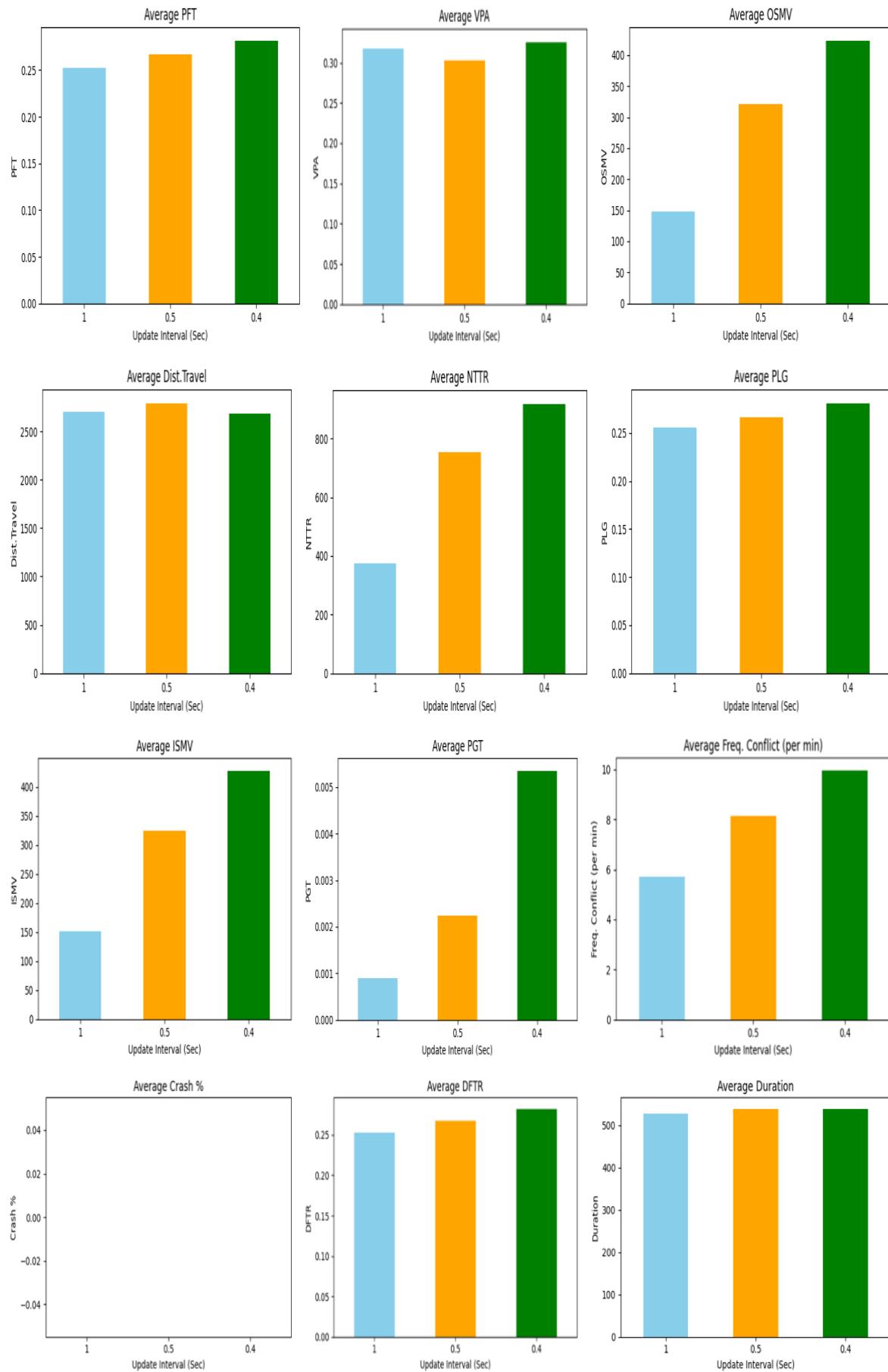
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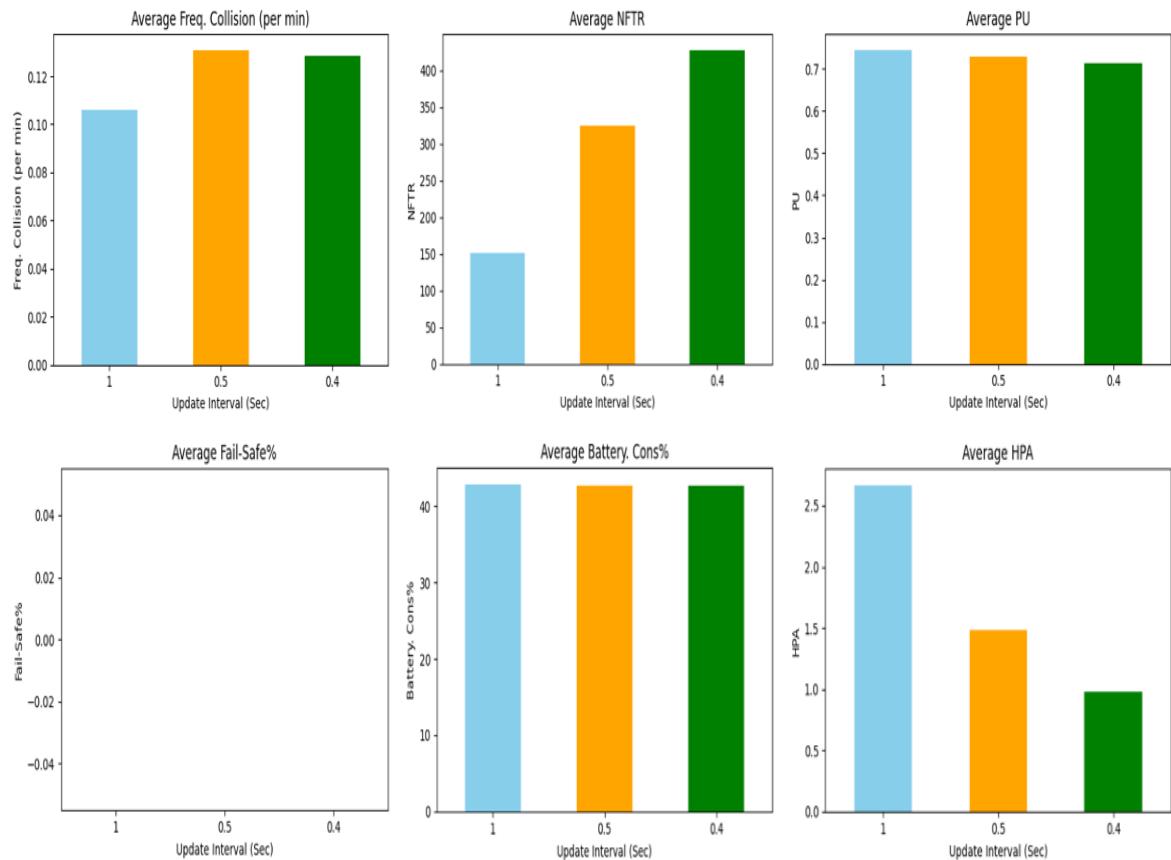
- **Impact of the different update intervals:**



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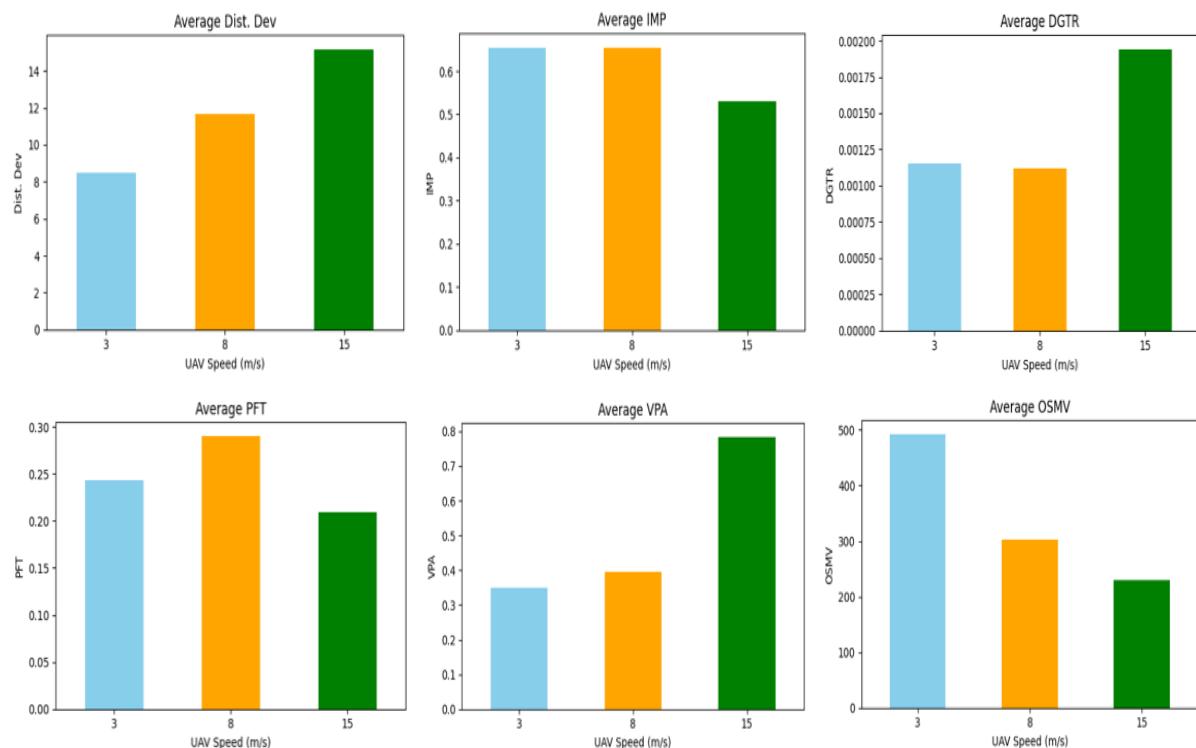


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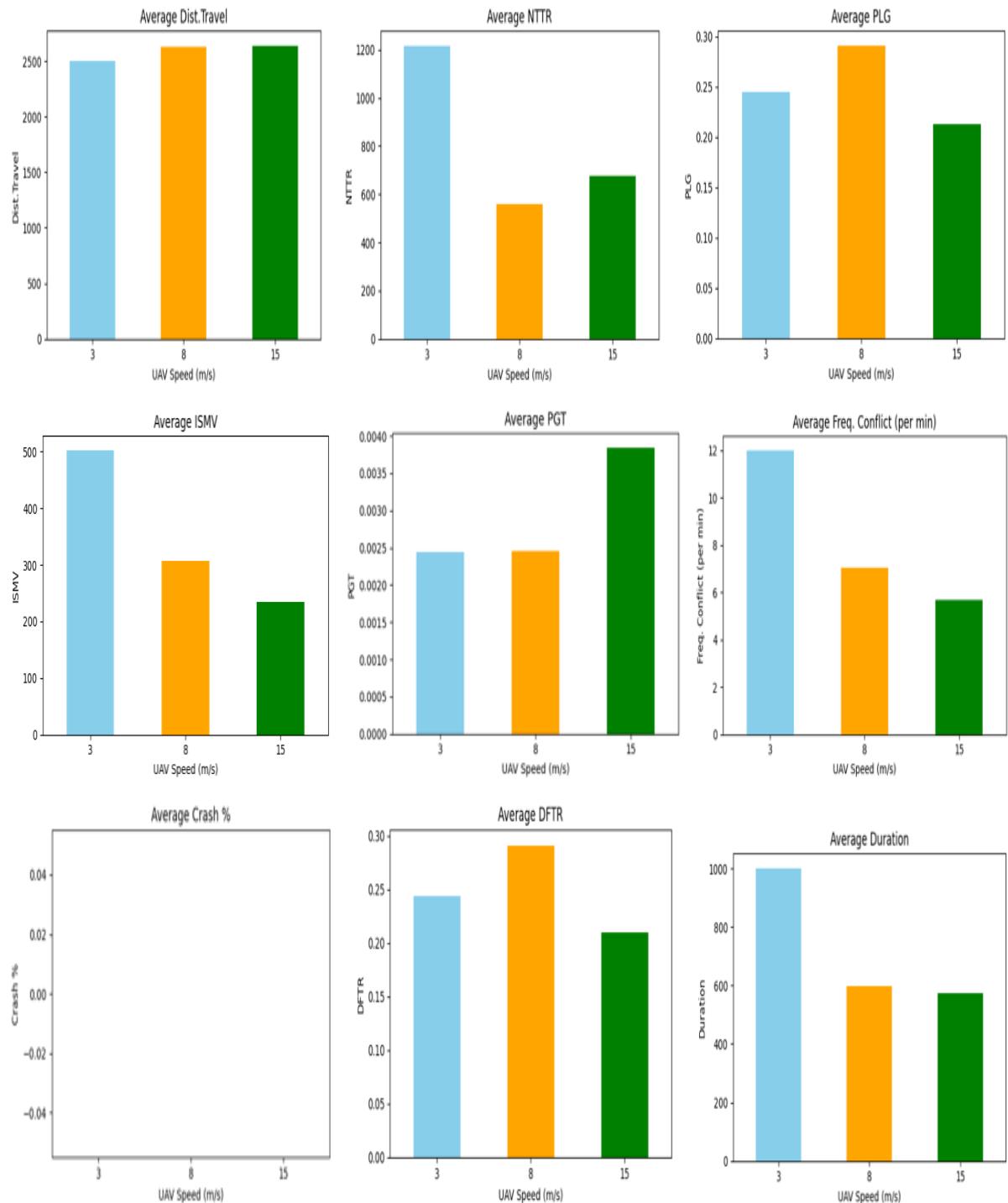


3) GPS Faults with near-gale wind conditions:

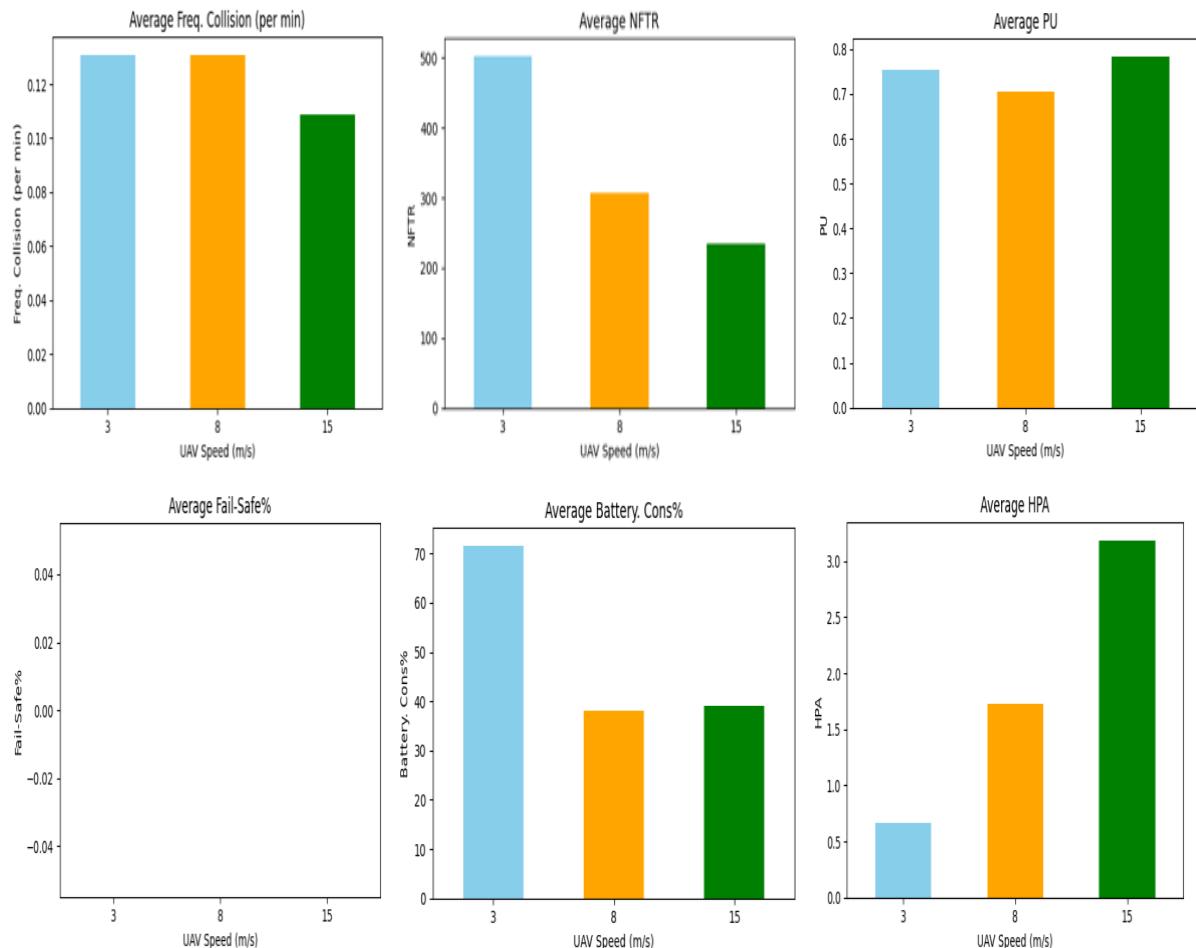
- Impact of the different UAV speeds:



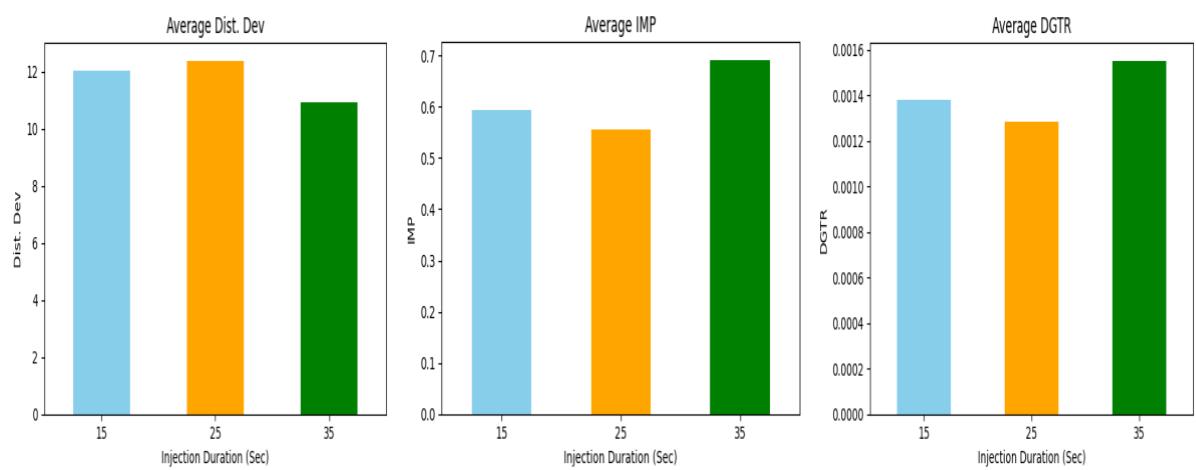
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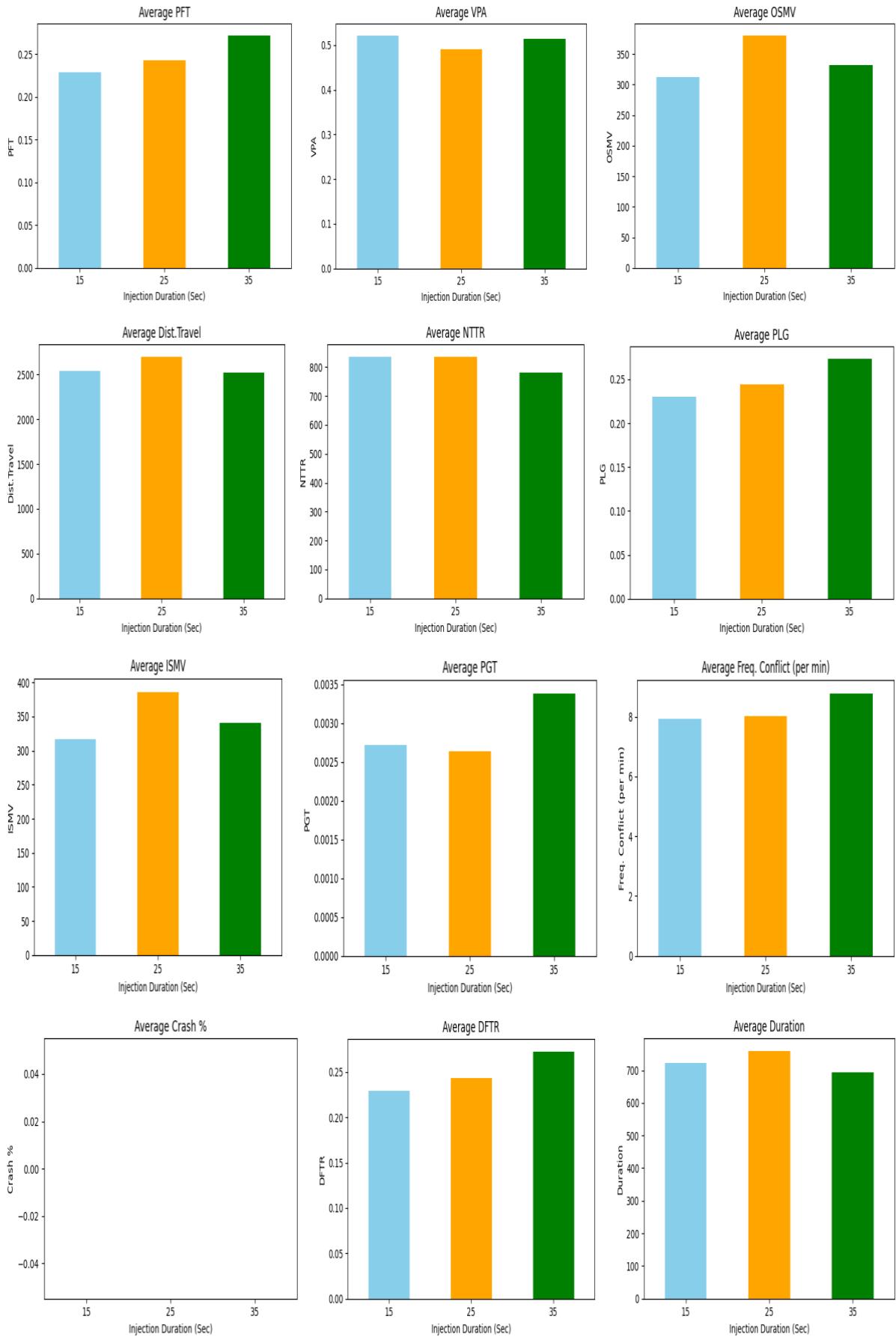
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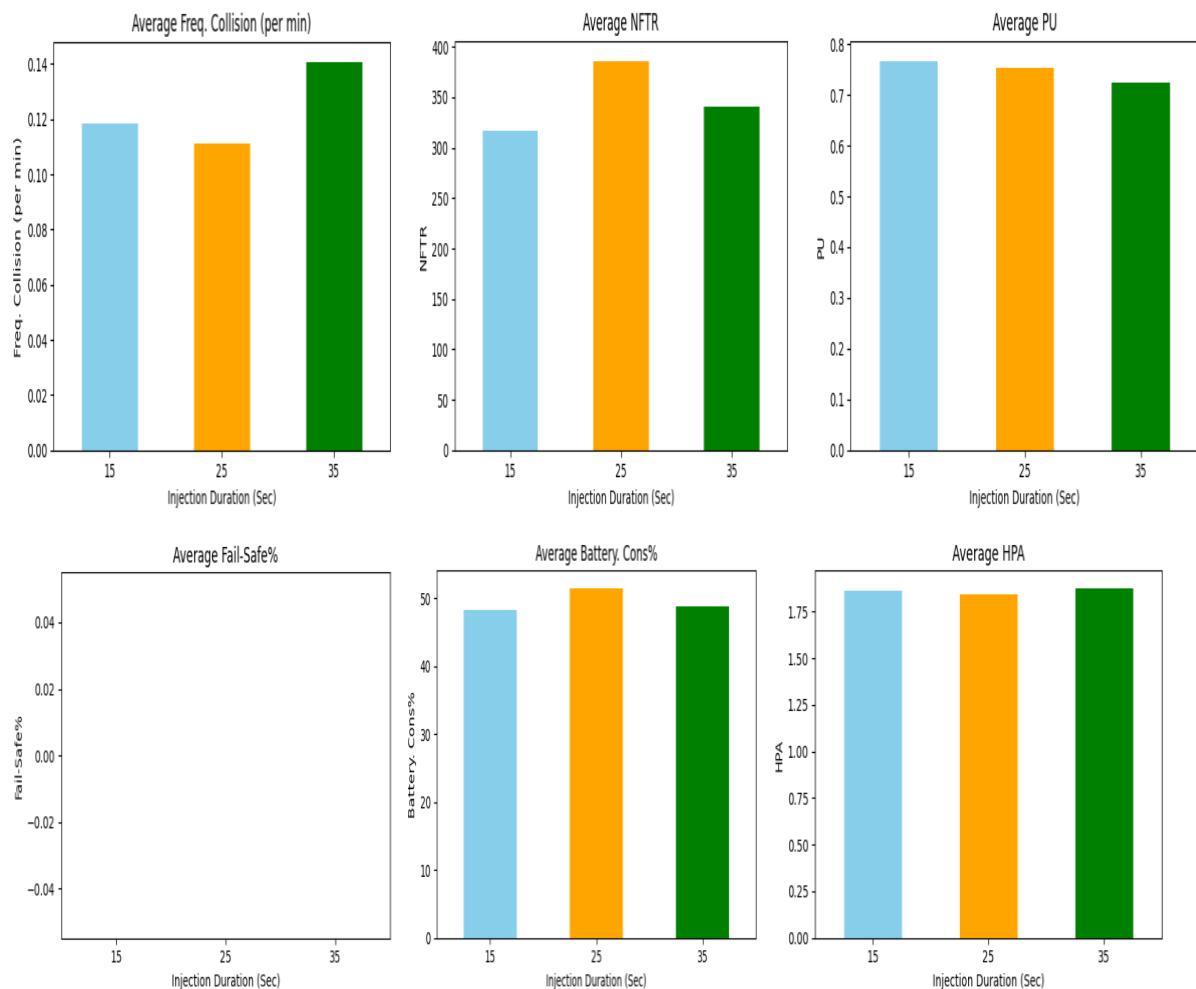
- **Impact of different injection durations:**



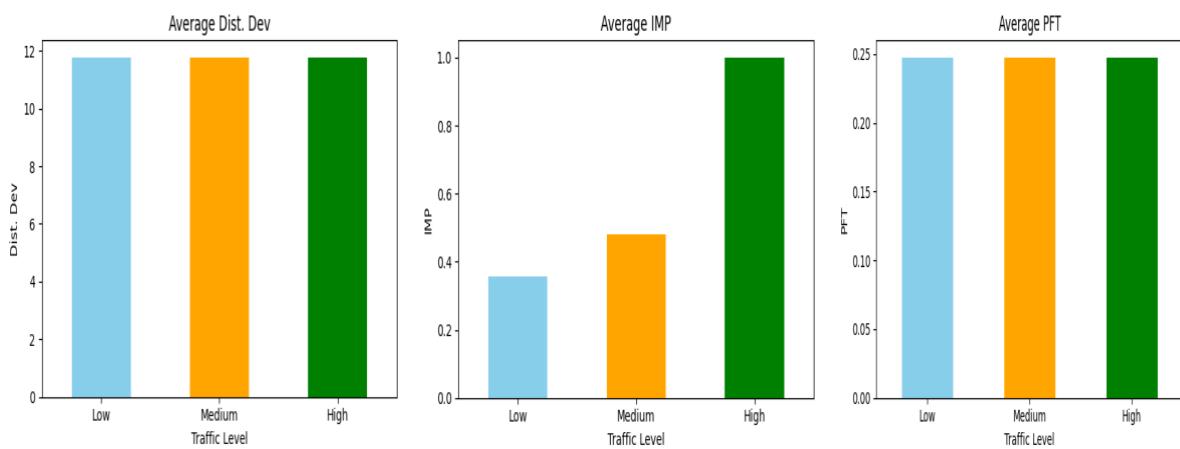
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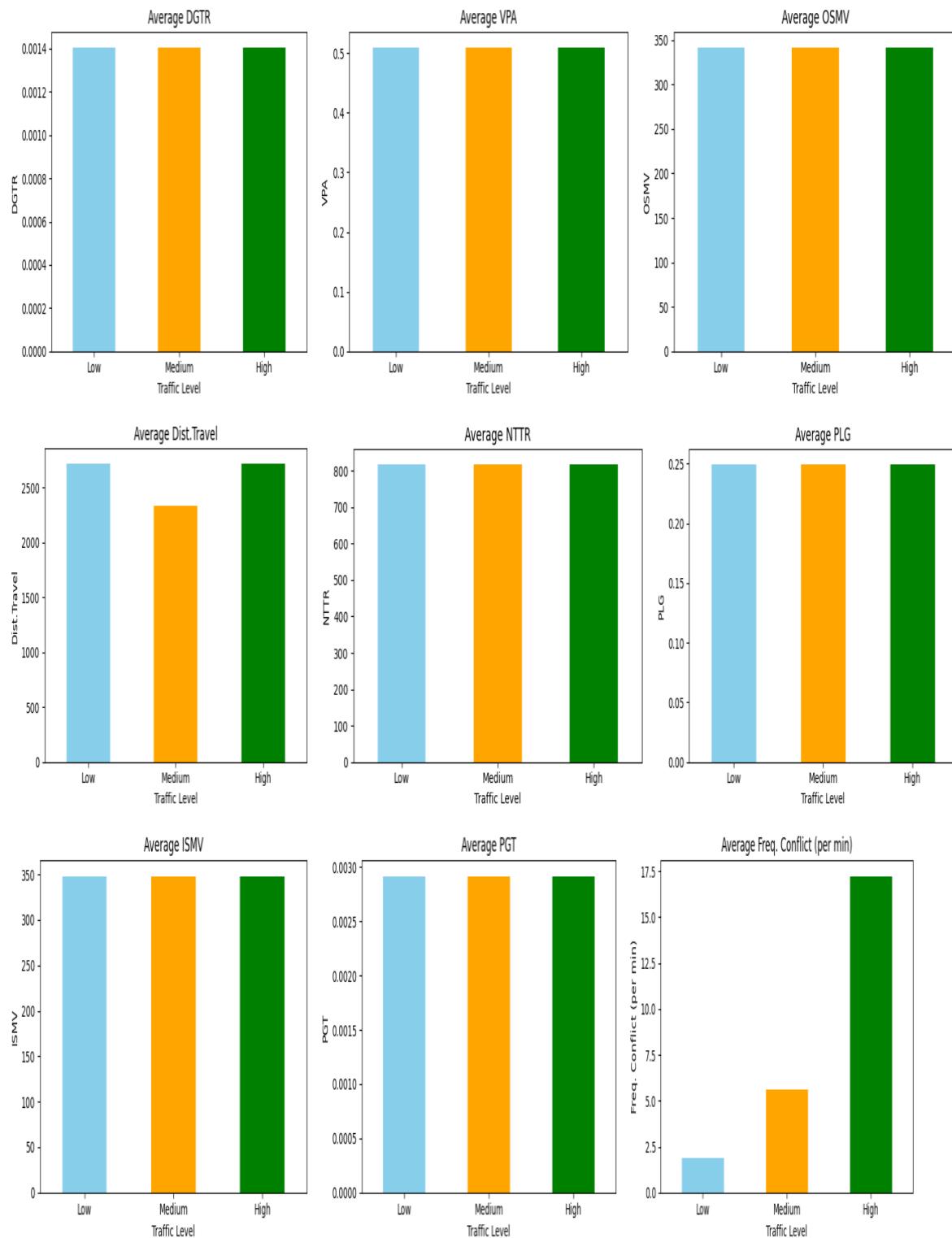
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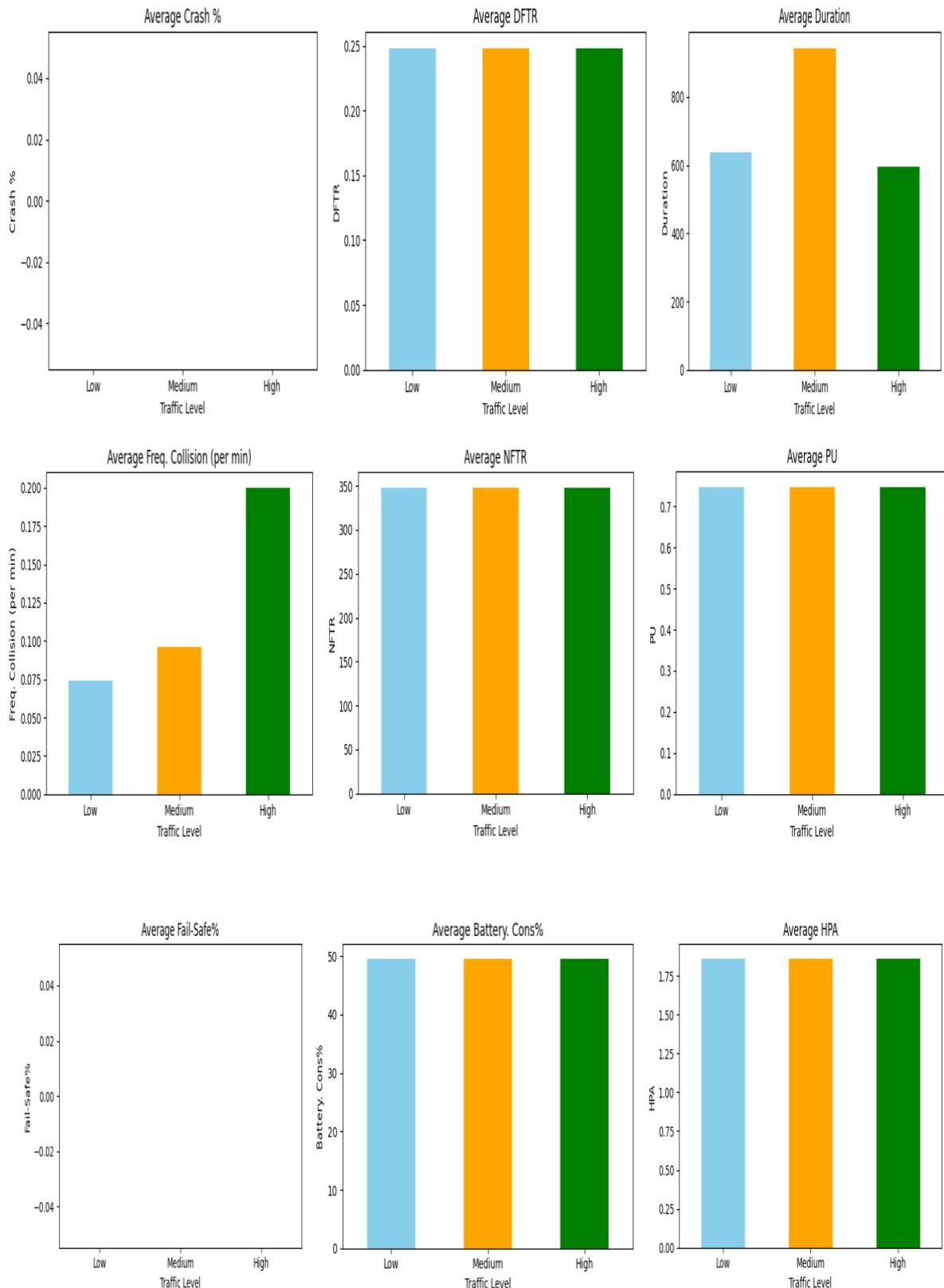
▪ Impact of different traffic levels:



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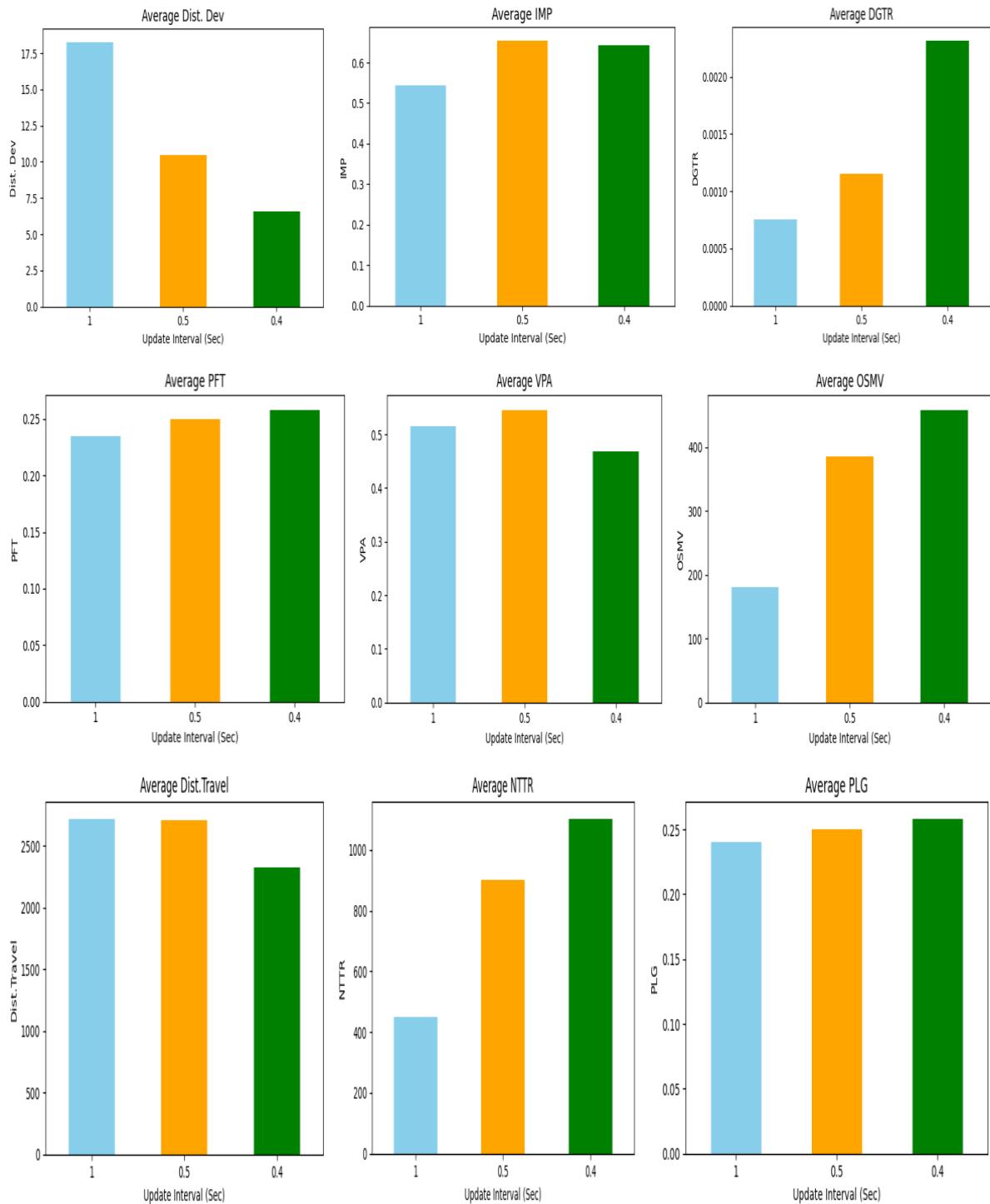


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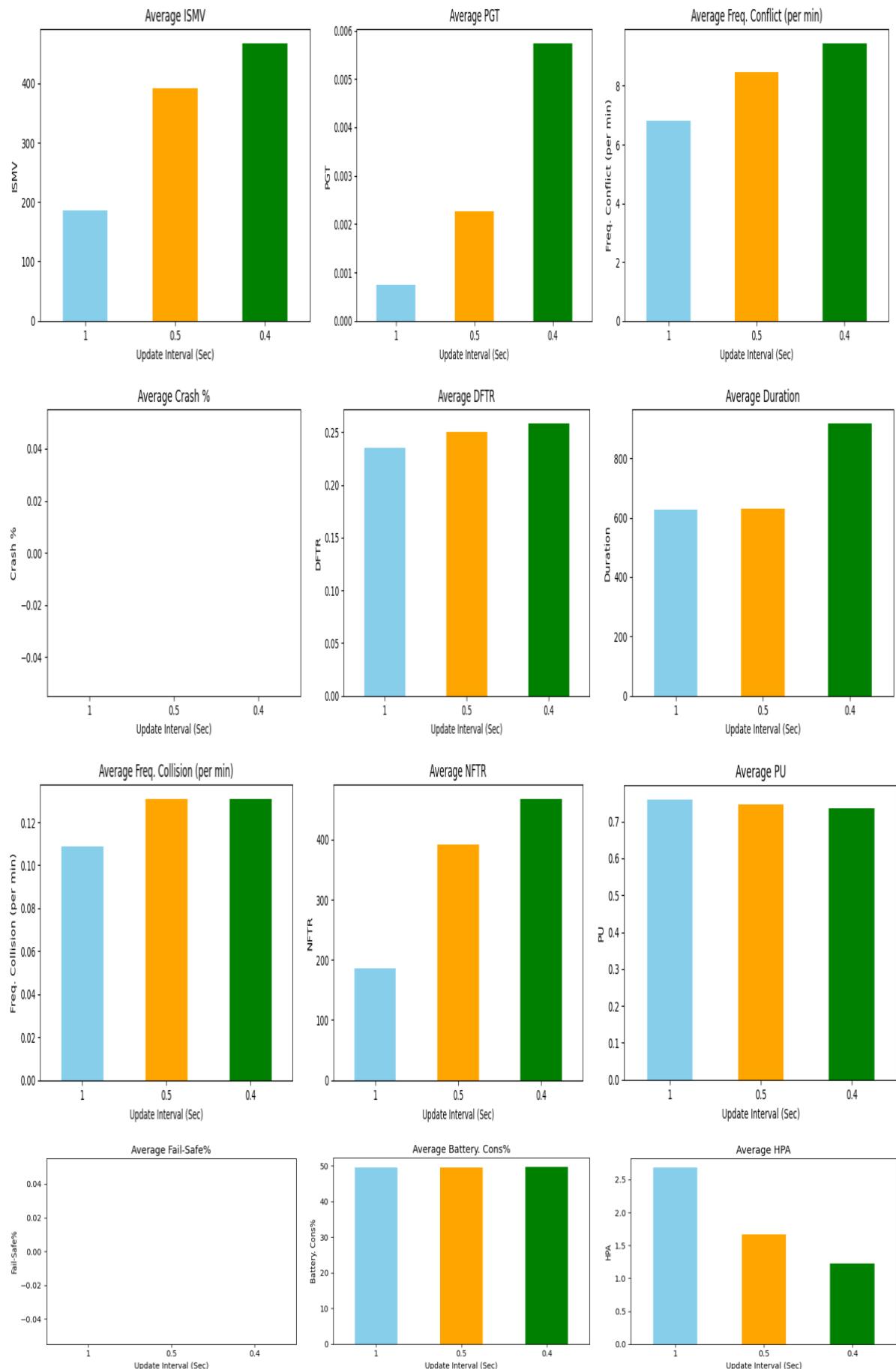


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- **Impact of different update intervals:**



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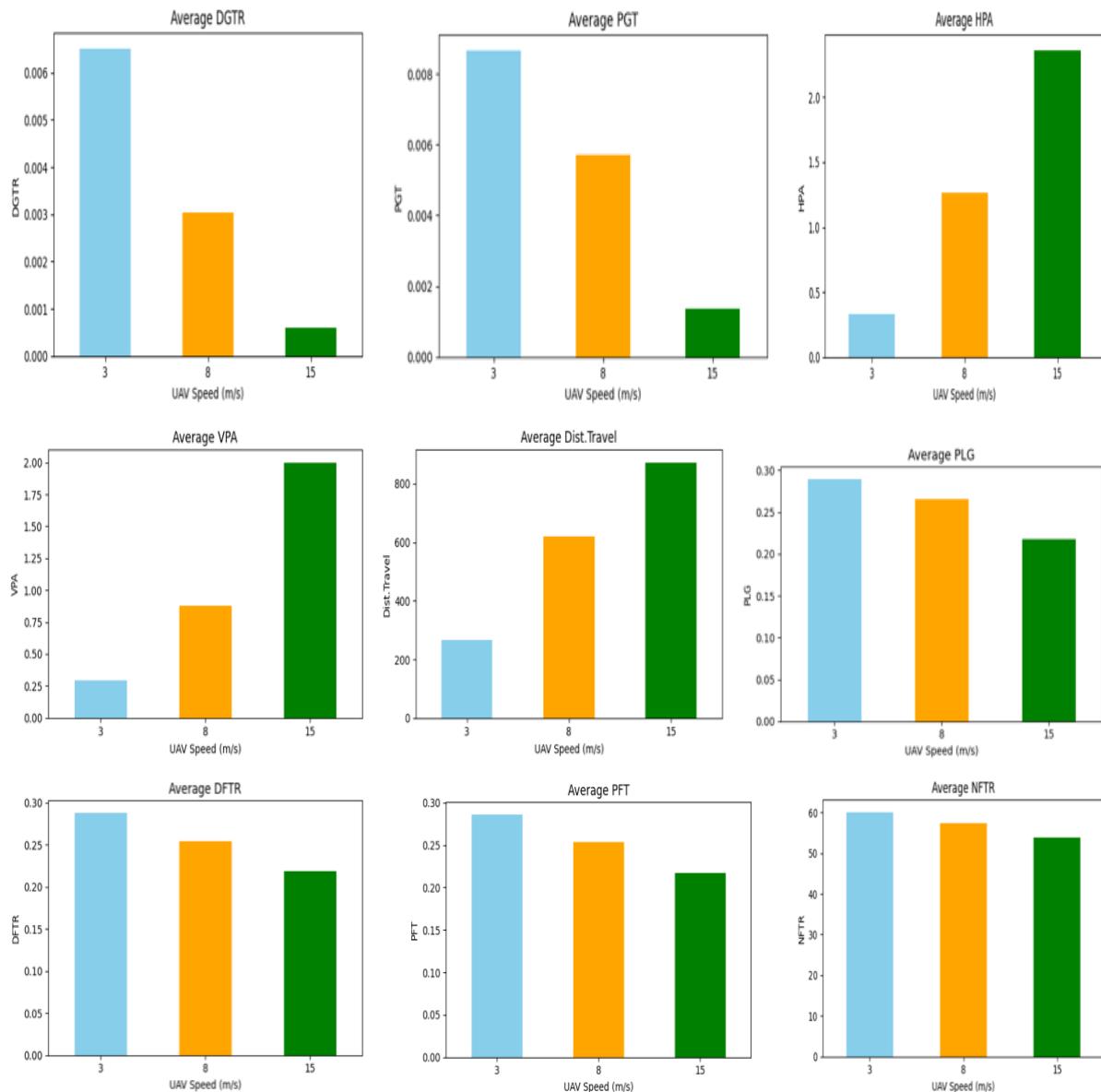


Impact of the different factors on IMU:

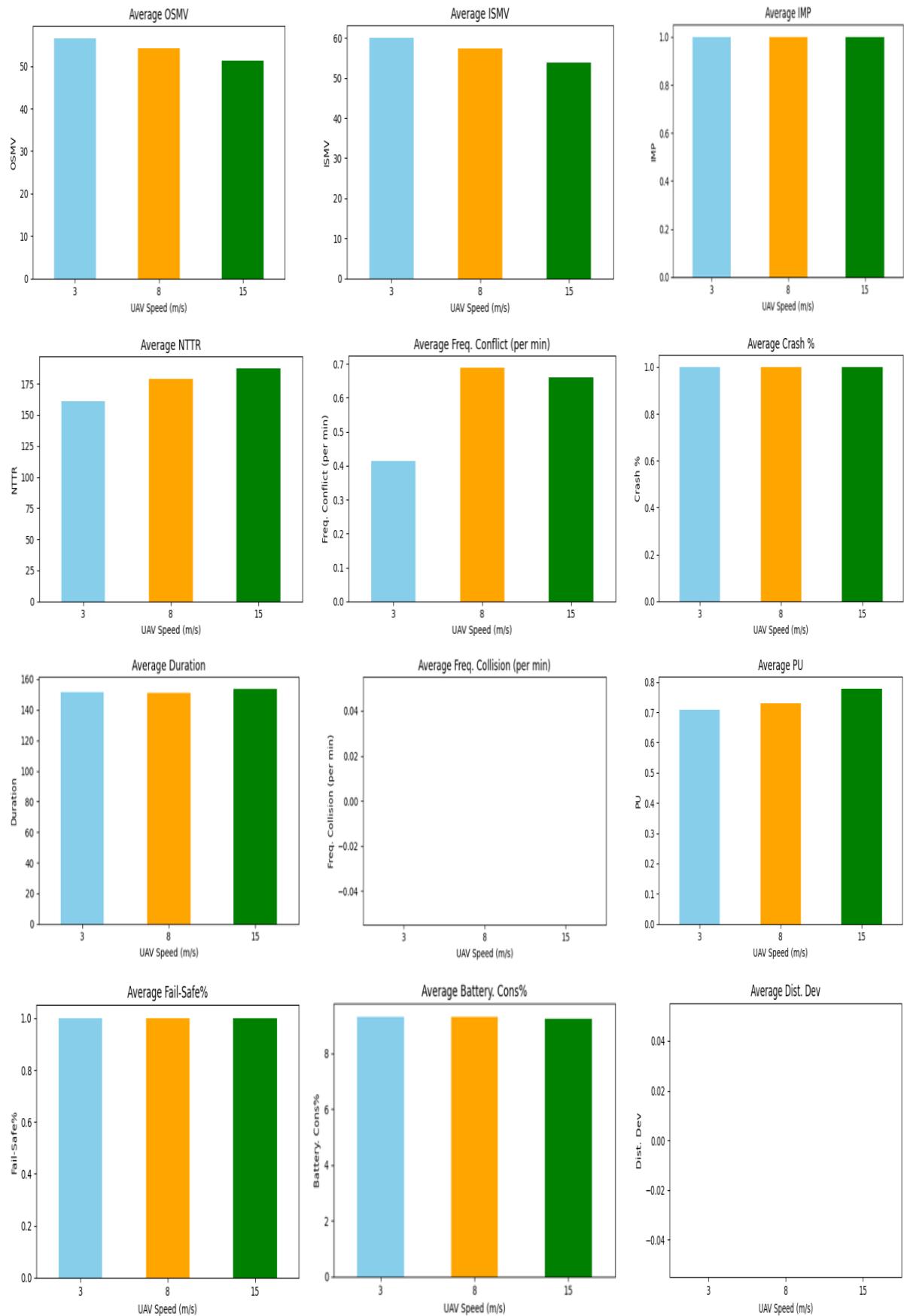
We injected three faults into the accelerometer and gyroscope including Maximum Value, Freeze Value, and Random Value and analyzed their effects on various safety metrics. Following the fault injection, we further examined how different operational factors, including UAV speeds, update intervals (UIs), traffic levels, and injection durations, as well as an environmental factor (wind), influenced these metrics.

1) Accelerometer faults with light breeze wind:

- Impact of the different UAV speeds:

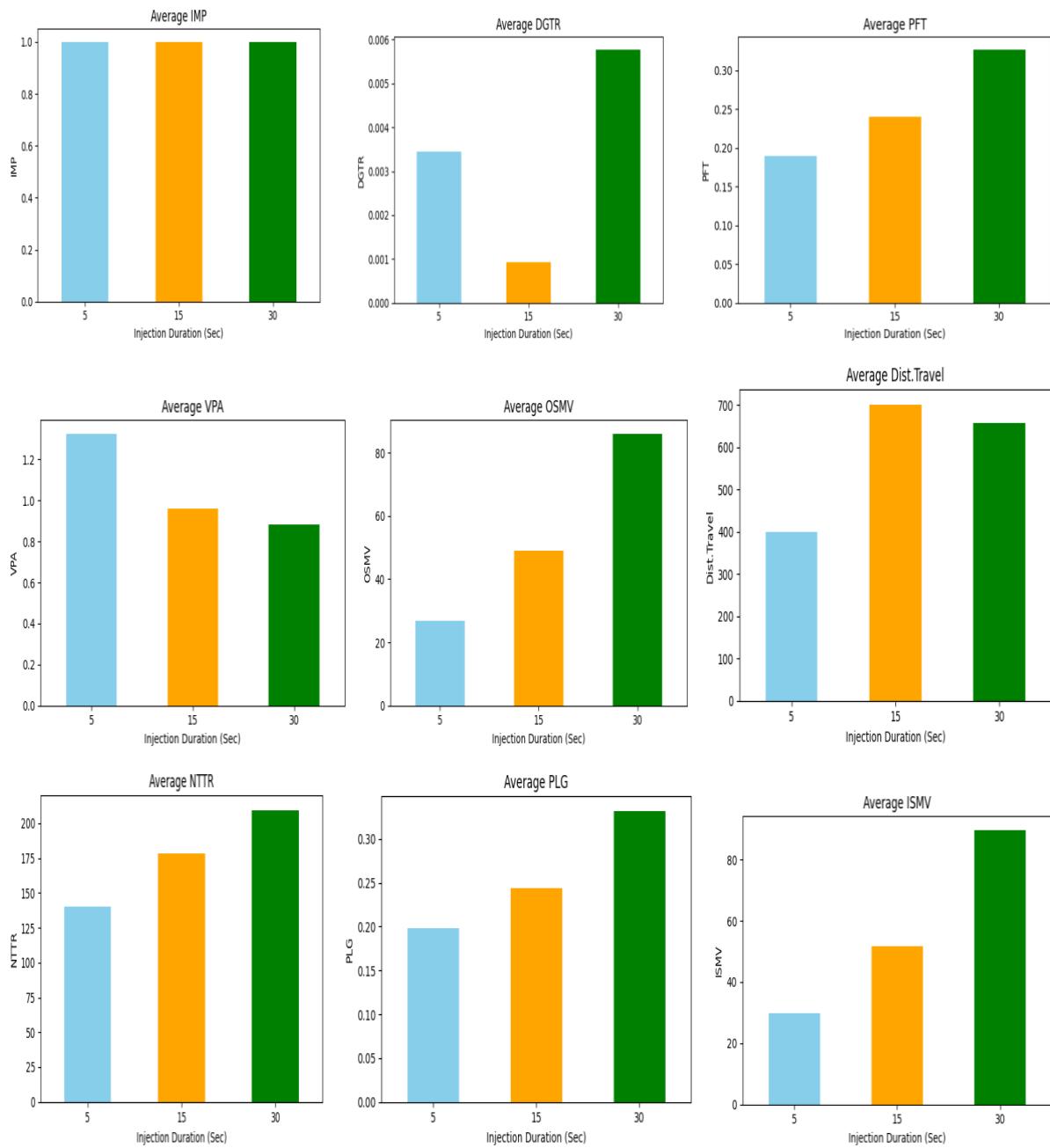


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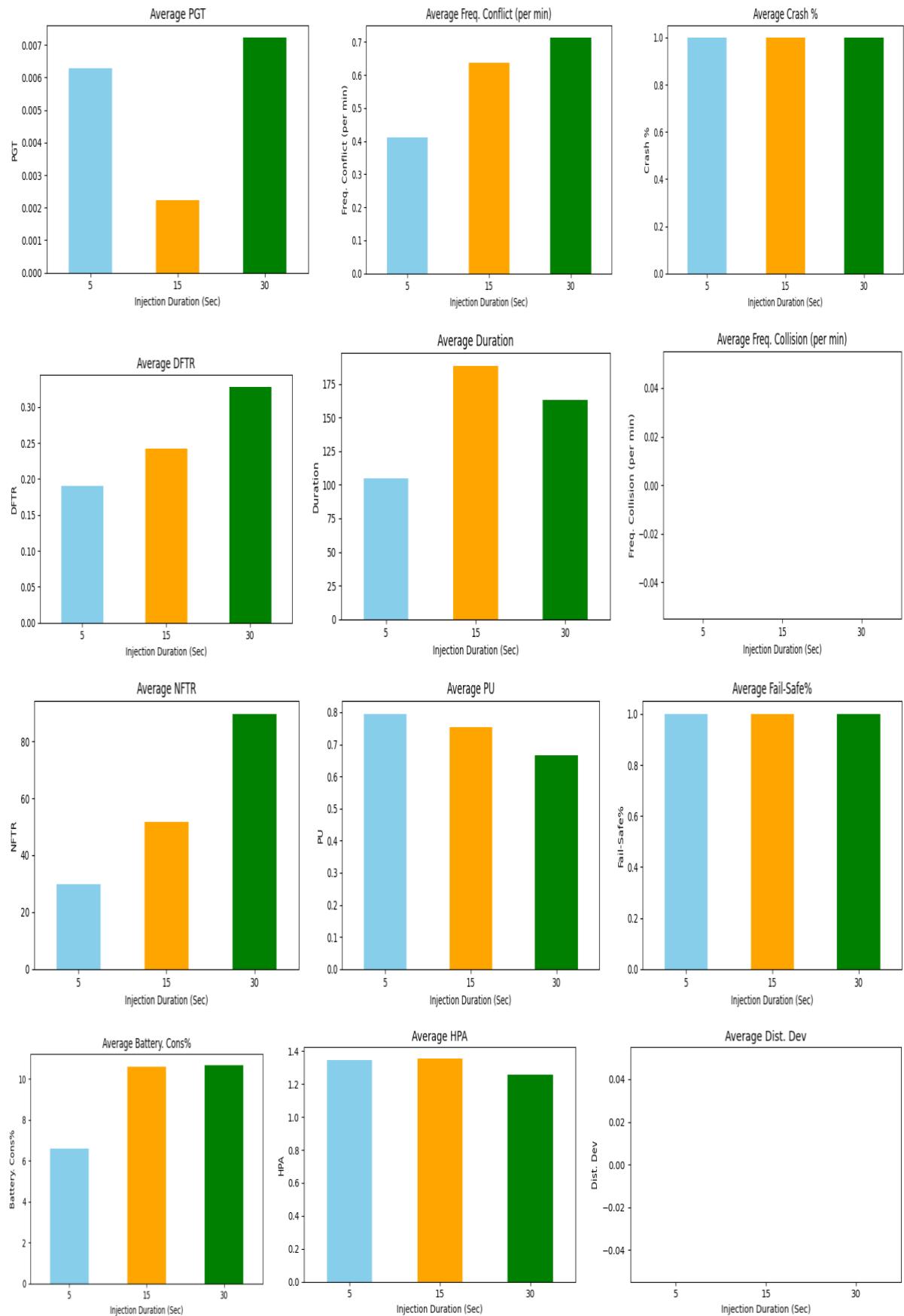


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- **Impact of the different injection durations:**

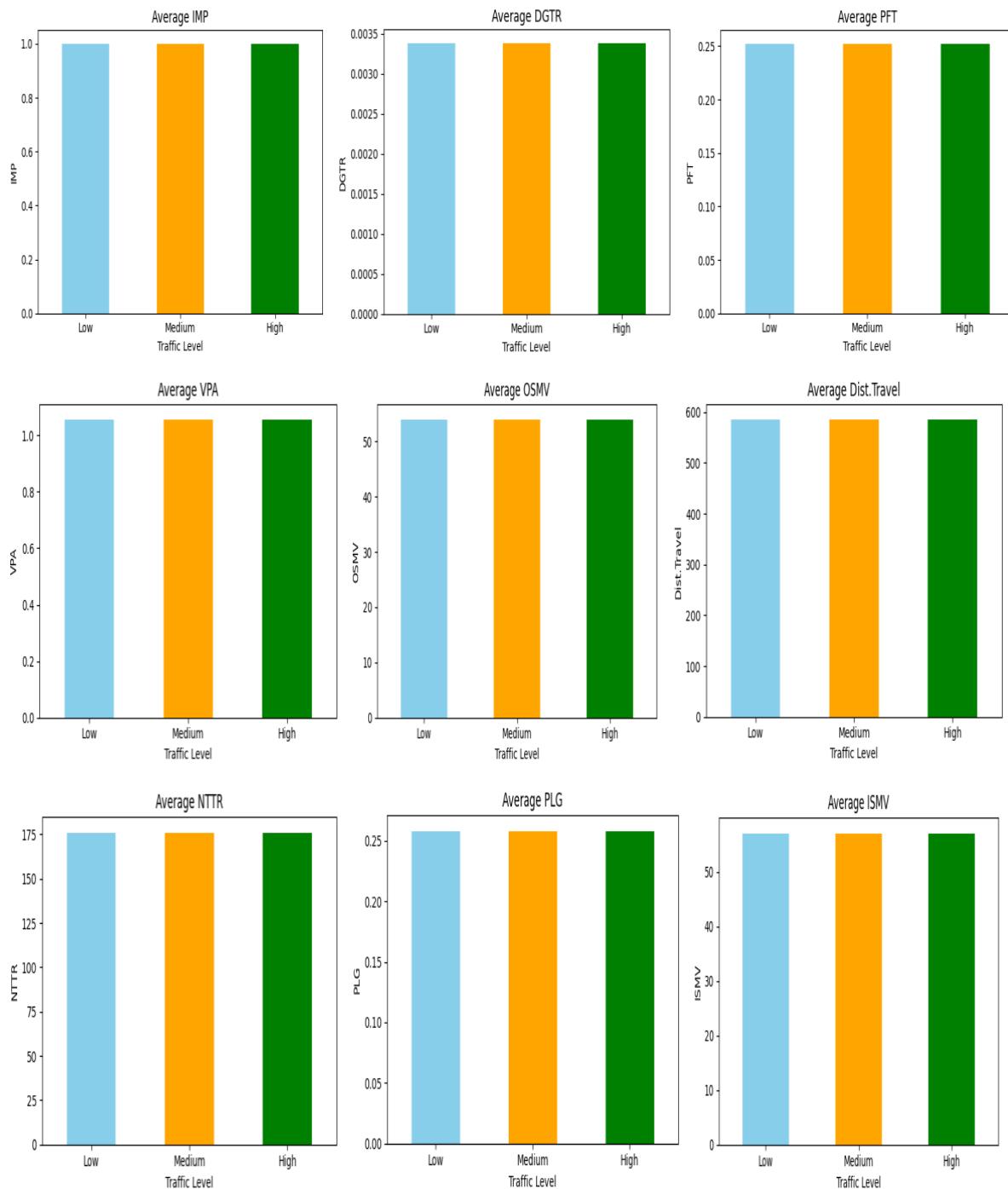


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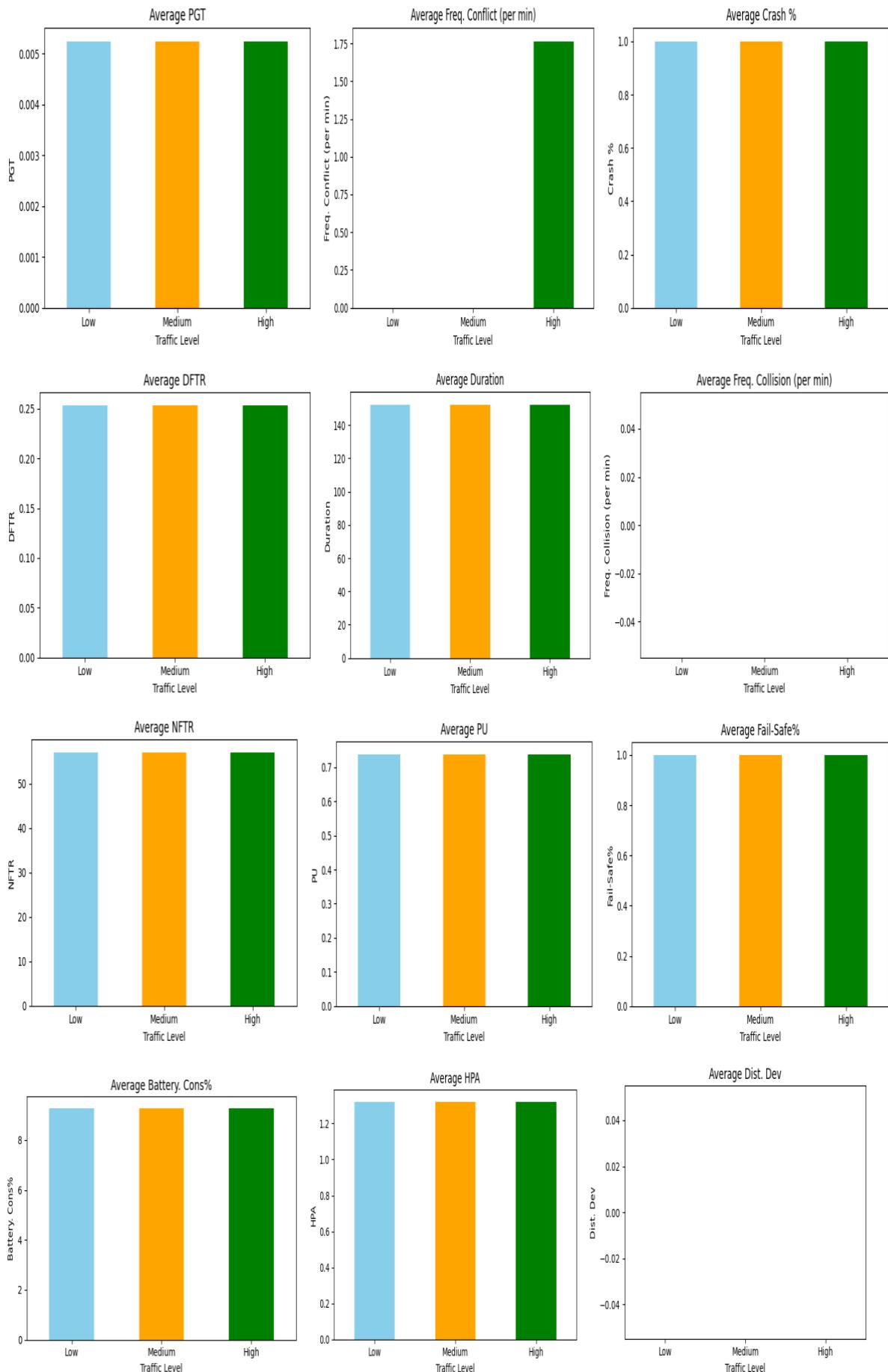


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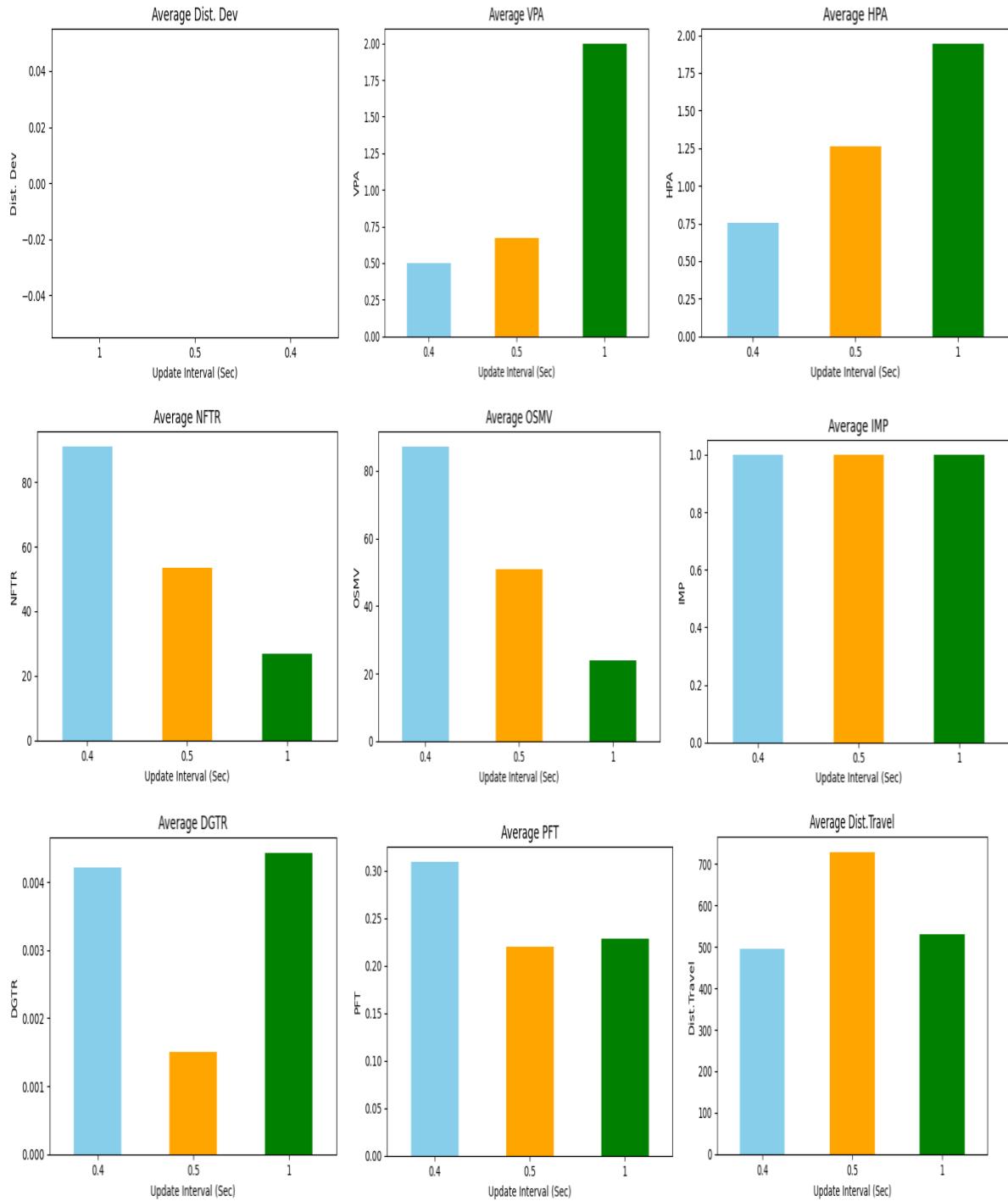
- **Impact of the different traffic levels:**



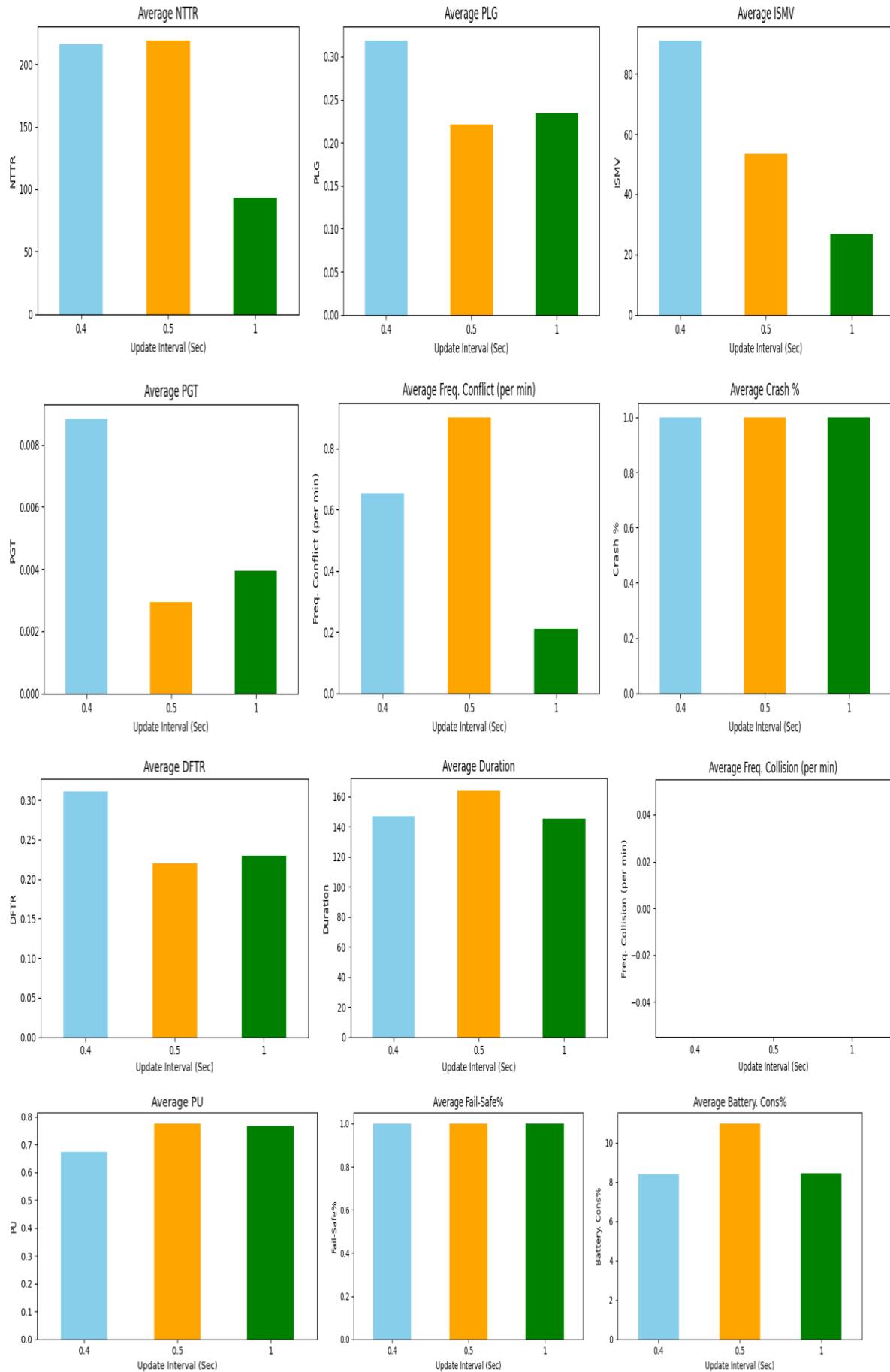
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- **Impact of the different Update Intervals:**

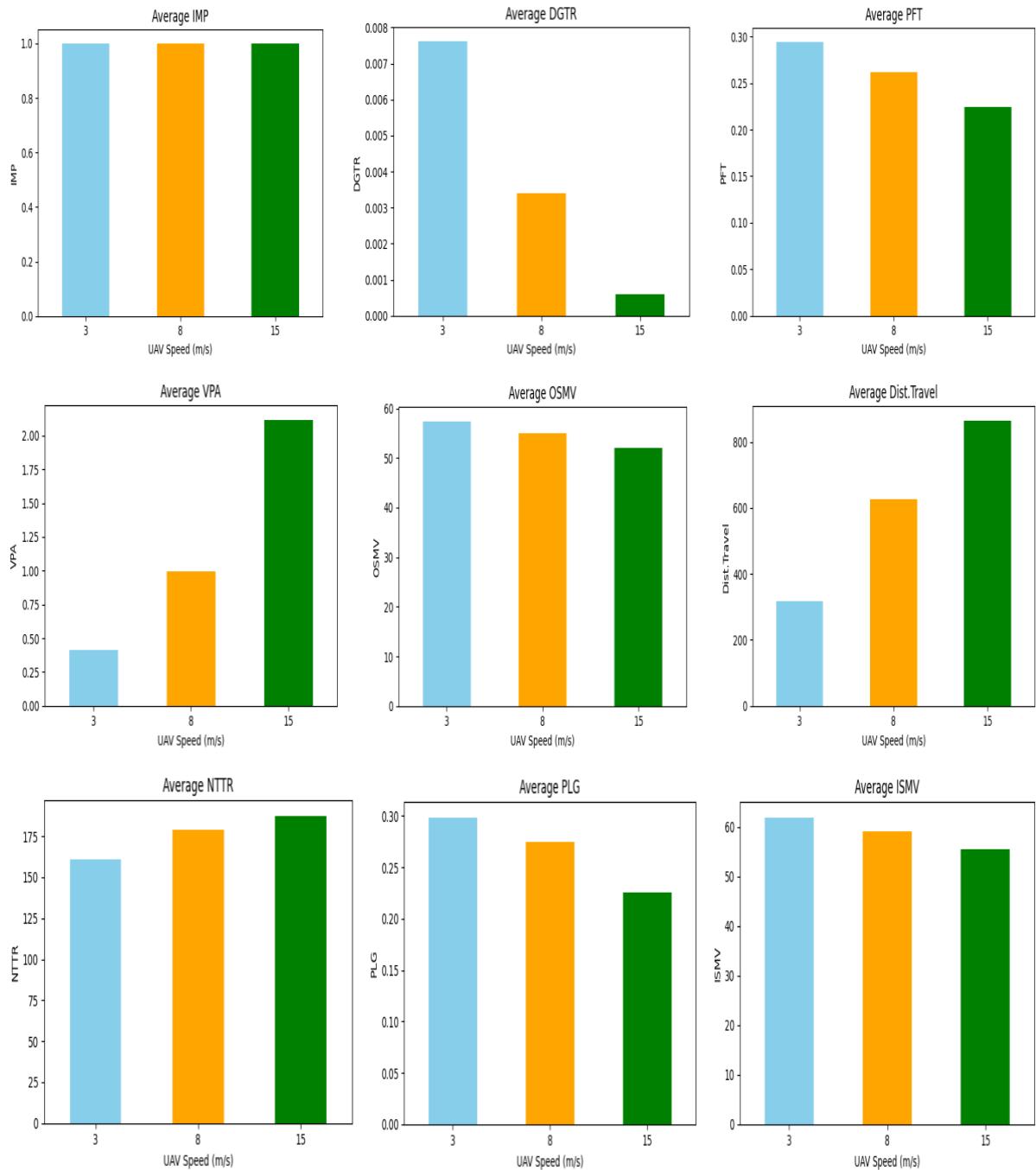


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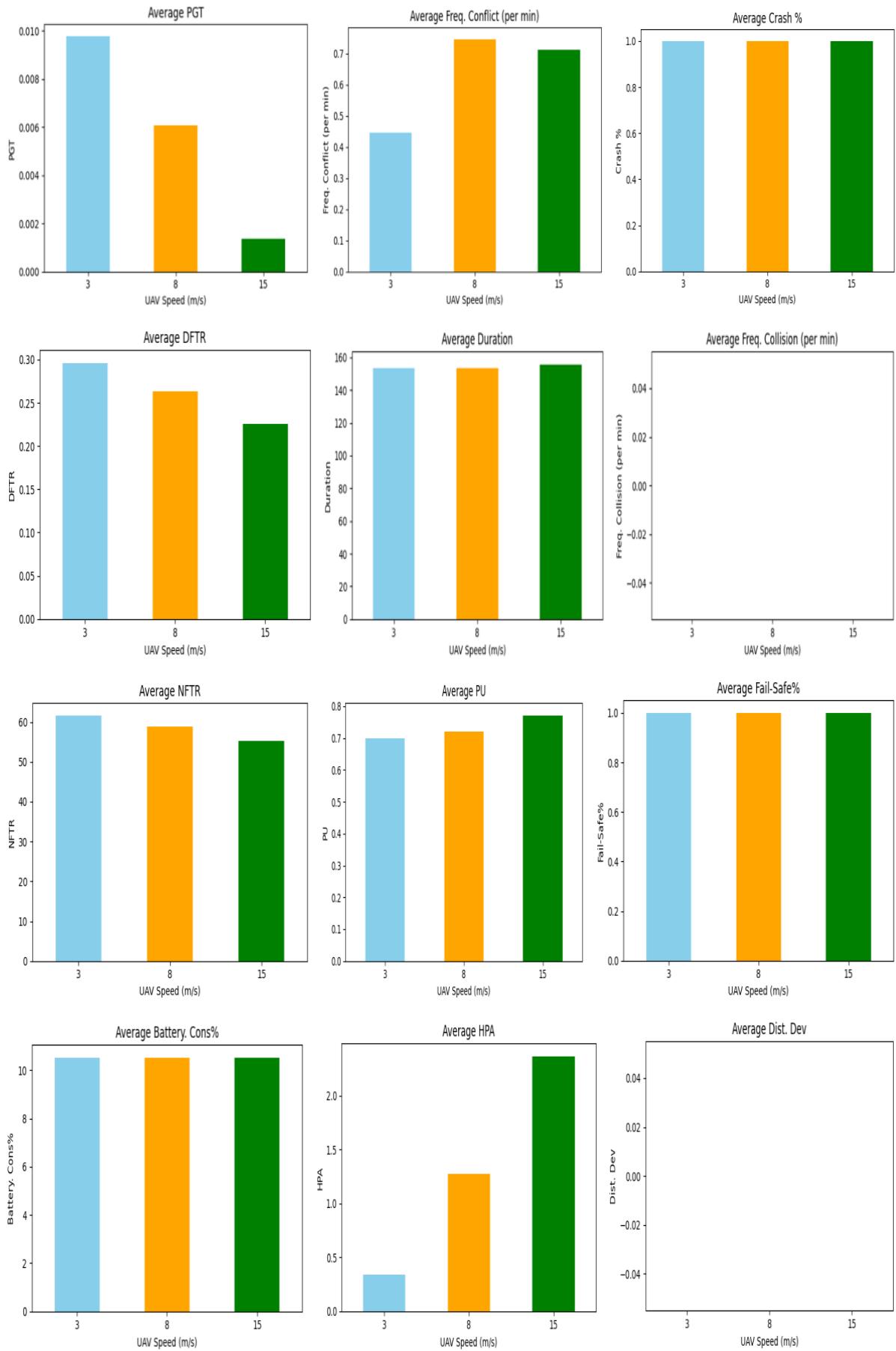


2) Accelerometer faults with moderate breeze wind:

- Impact of different UAV speeds:

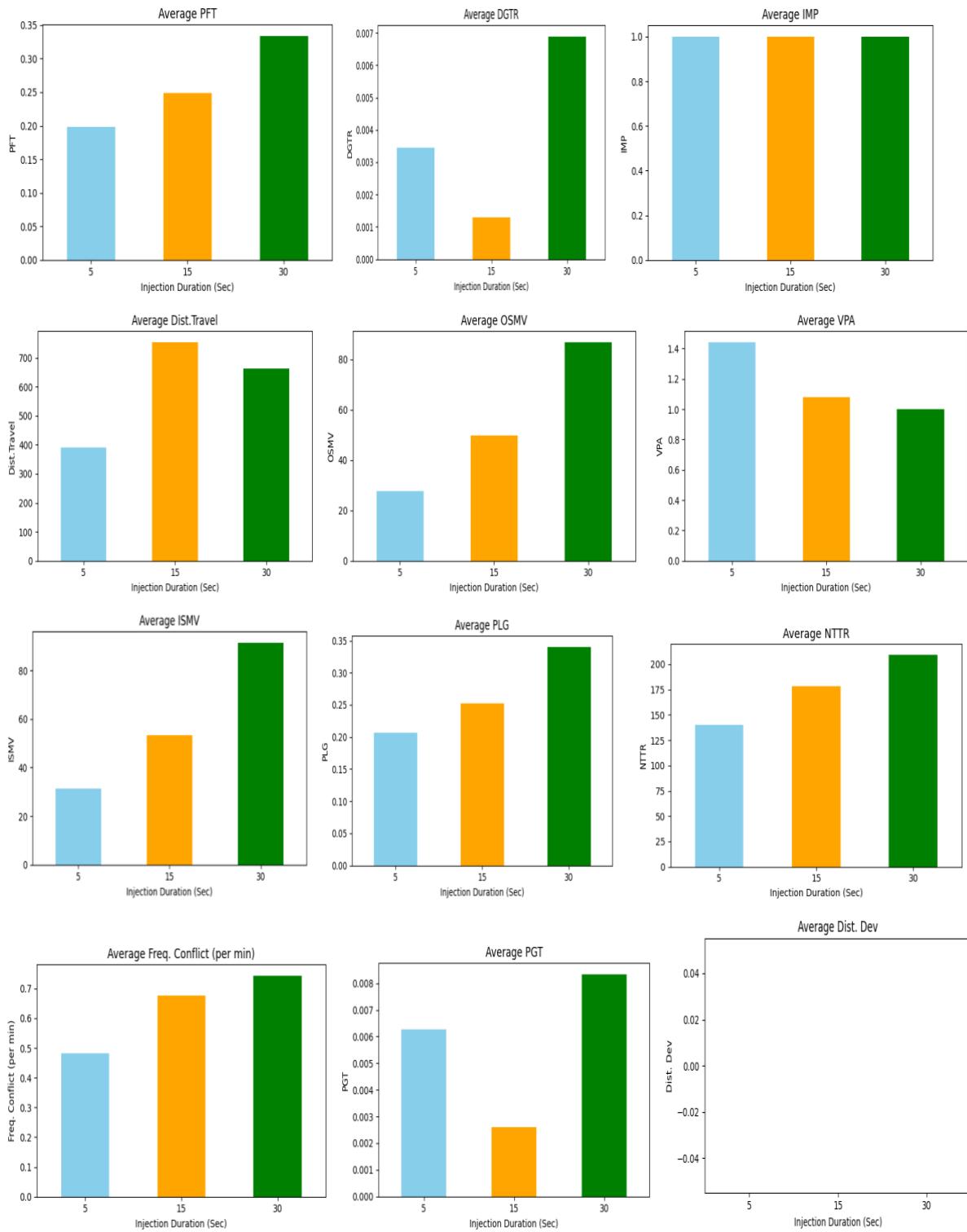


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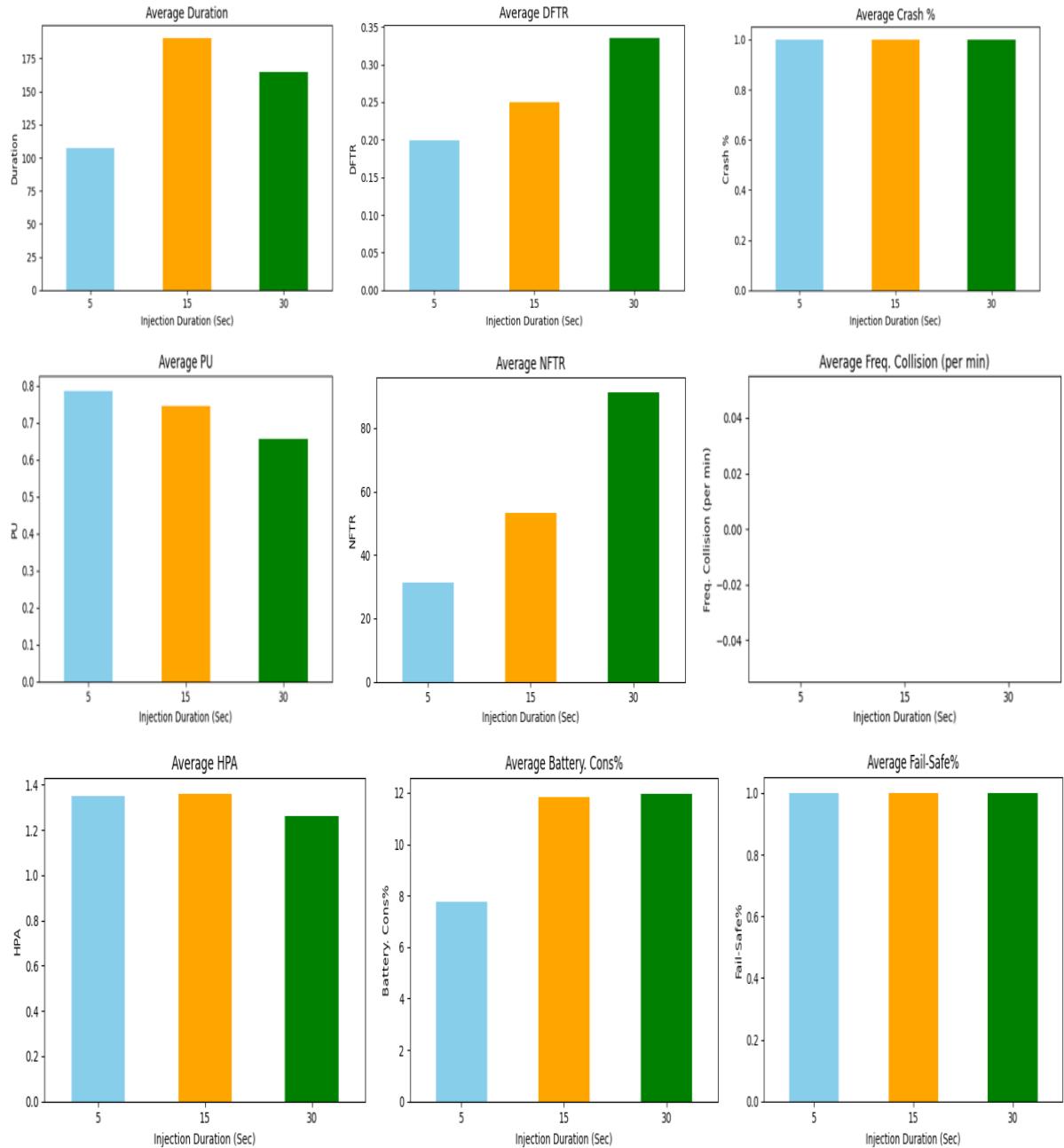


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- **Impact of different injection durations:**

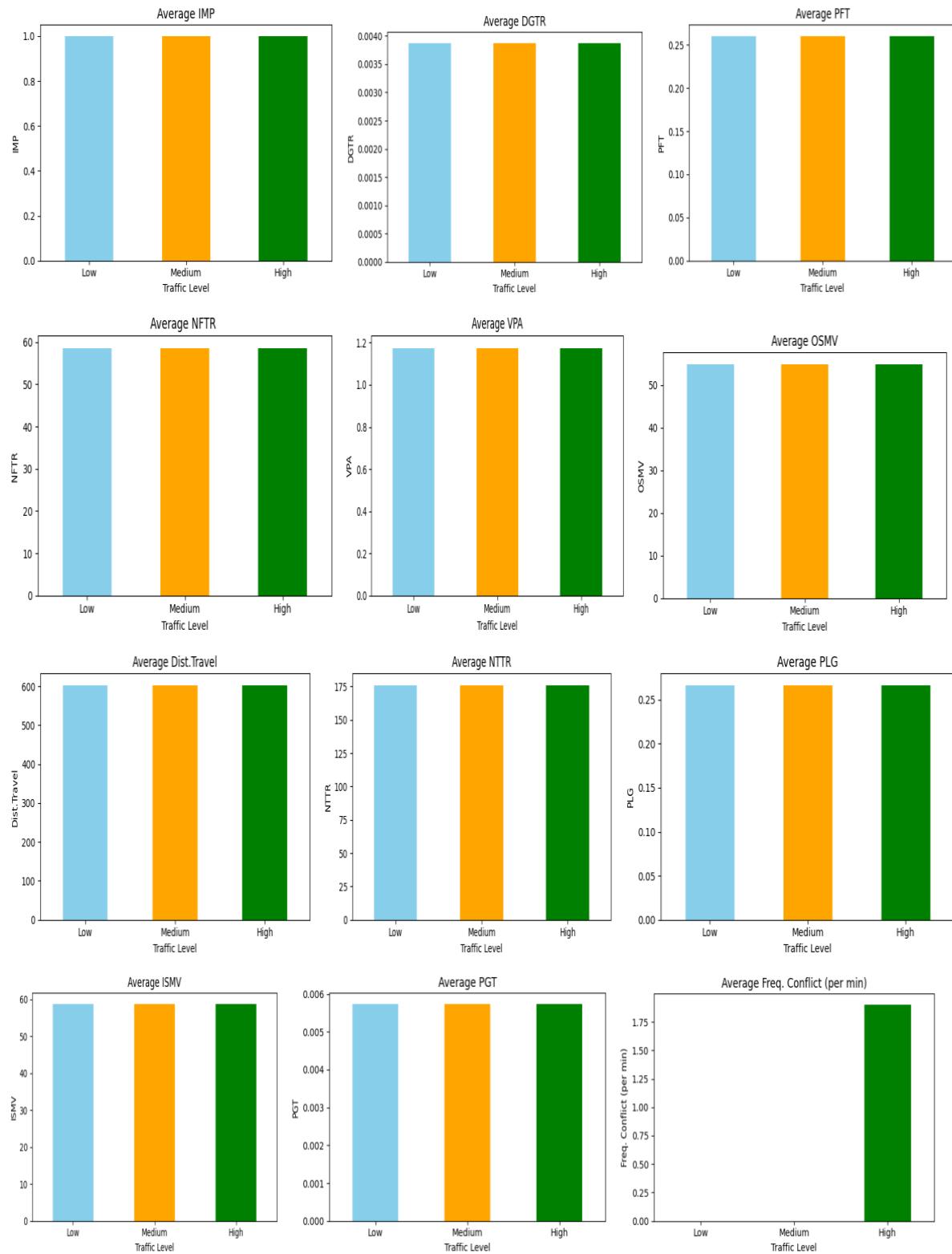


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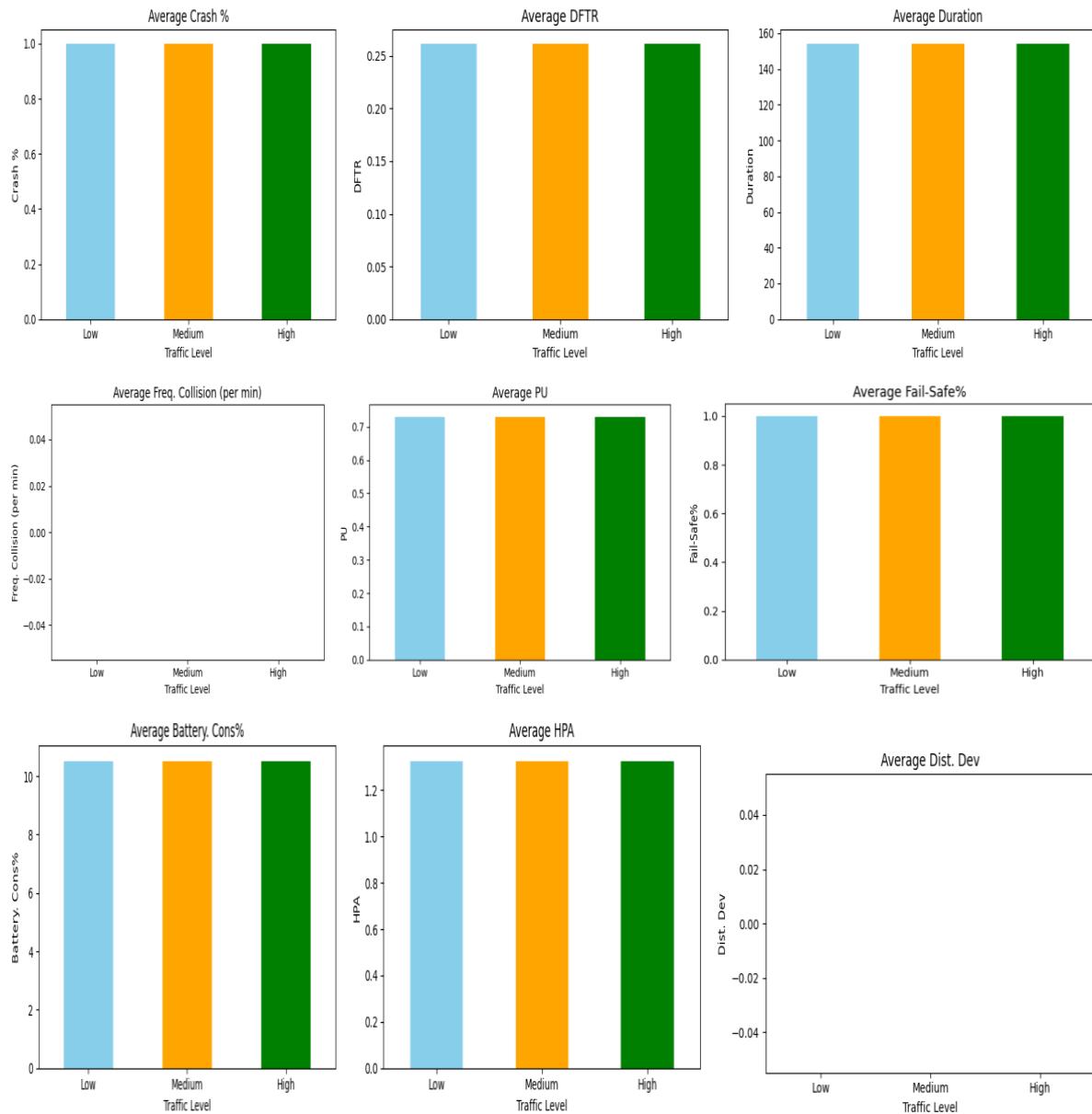


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- **Impact of different traffic levels:**

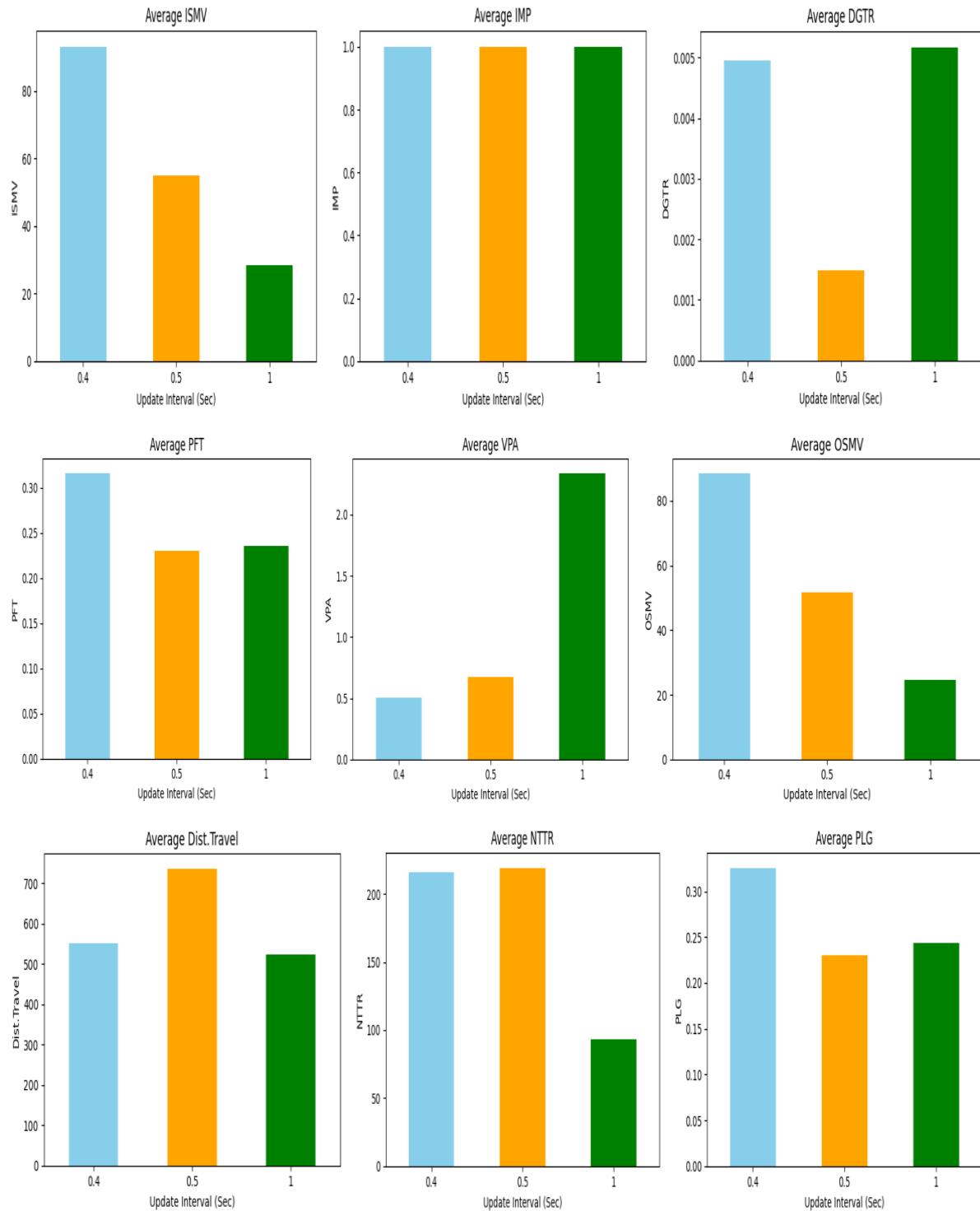


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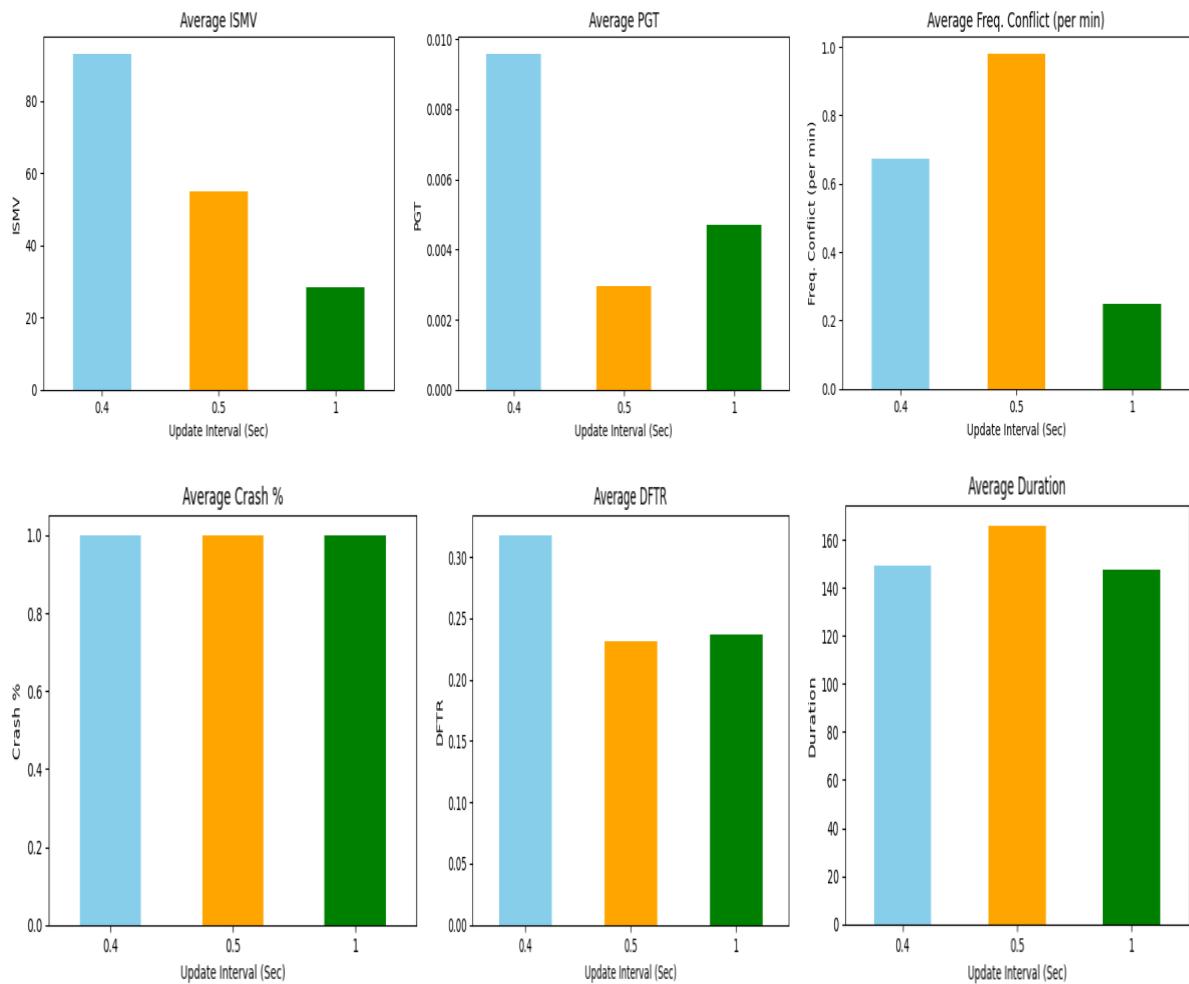


Technical Reports

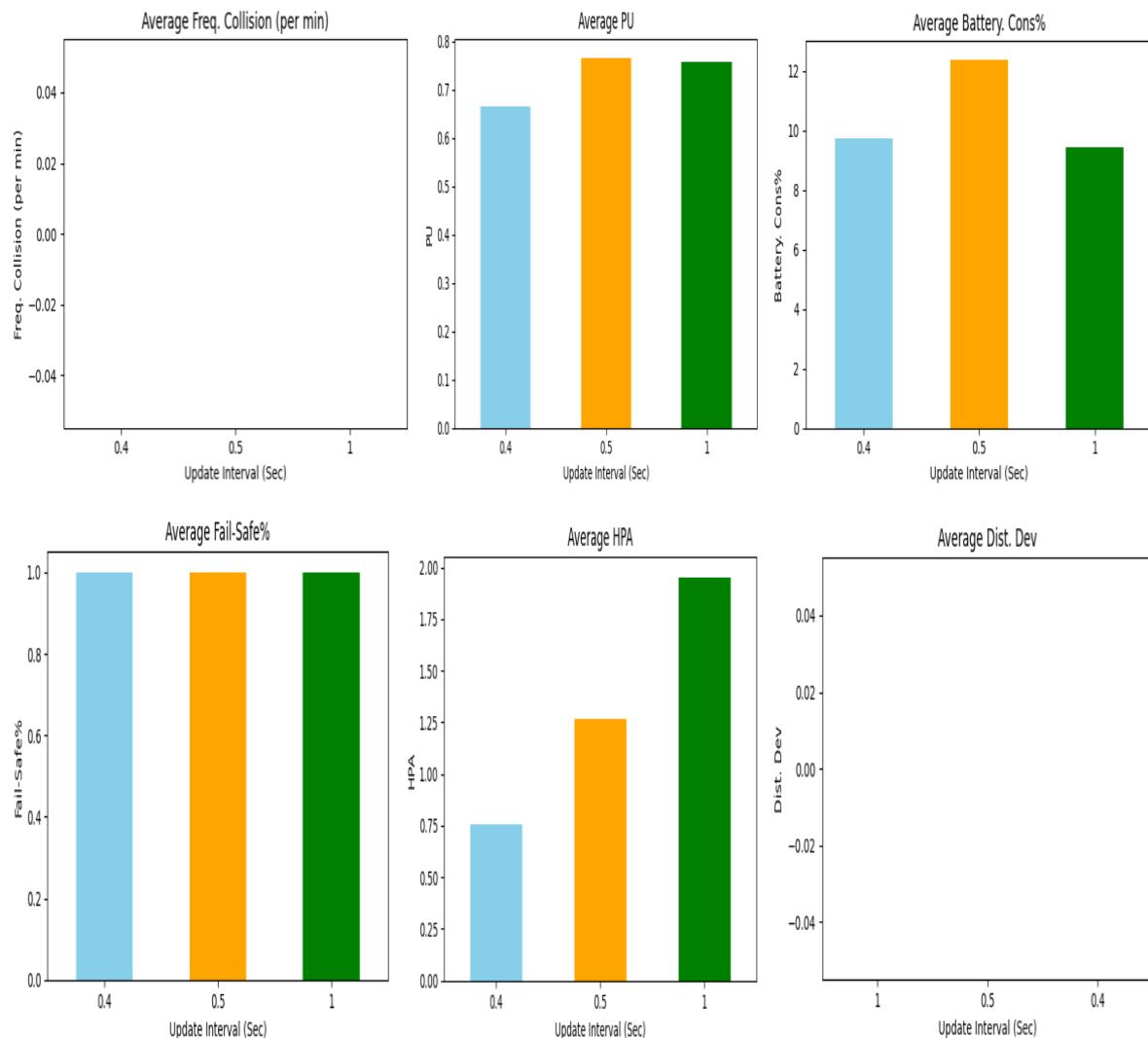
- **Impact of different update intervals:**



Technical Reports

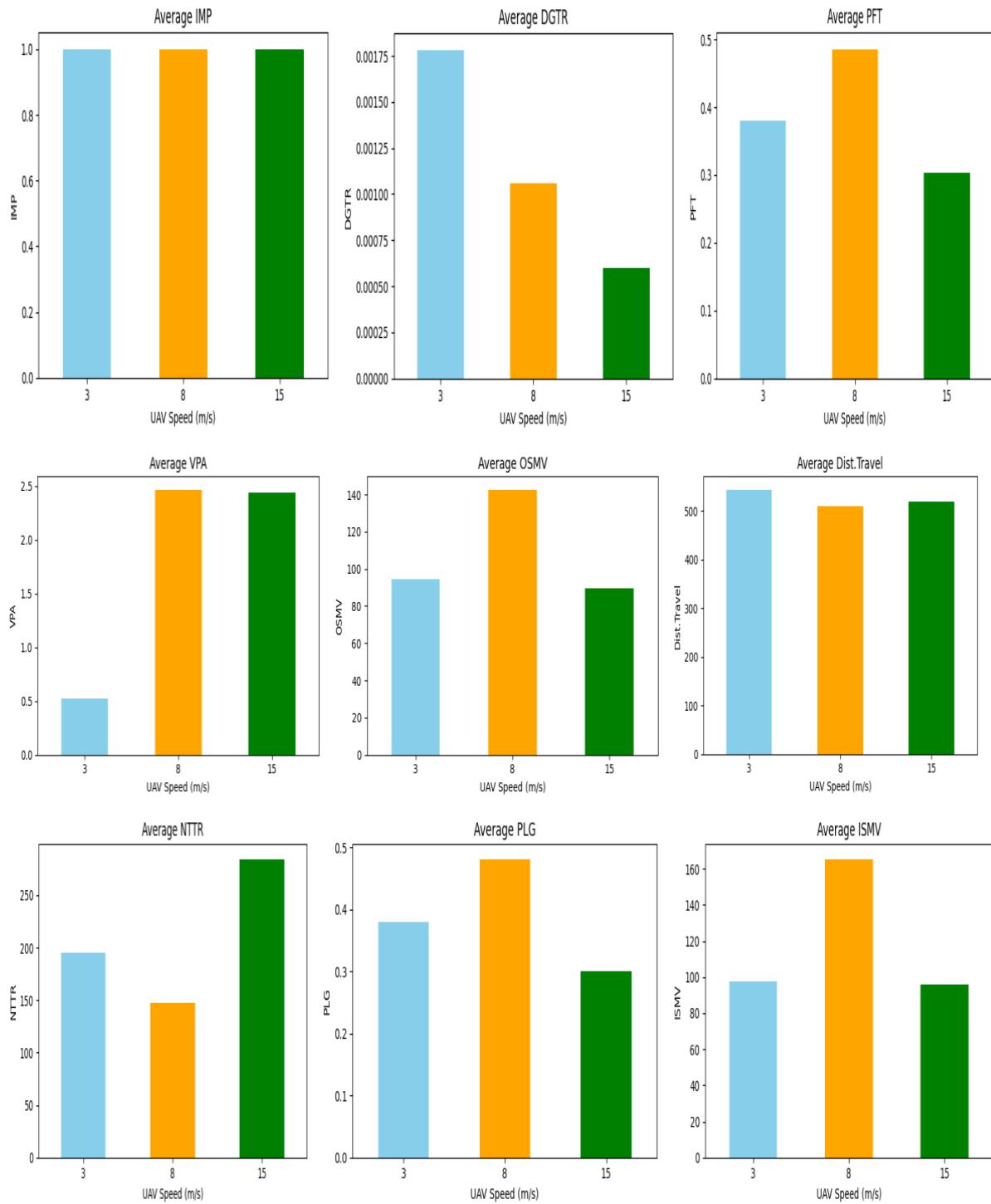


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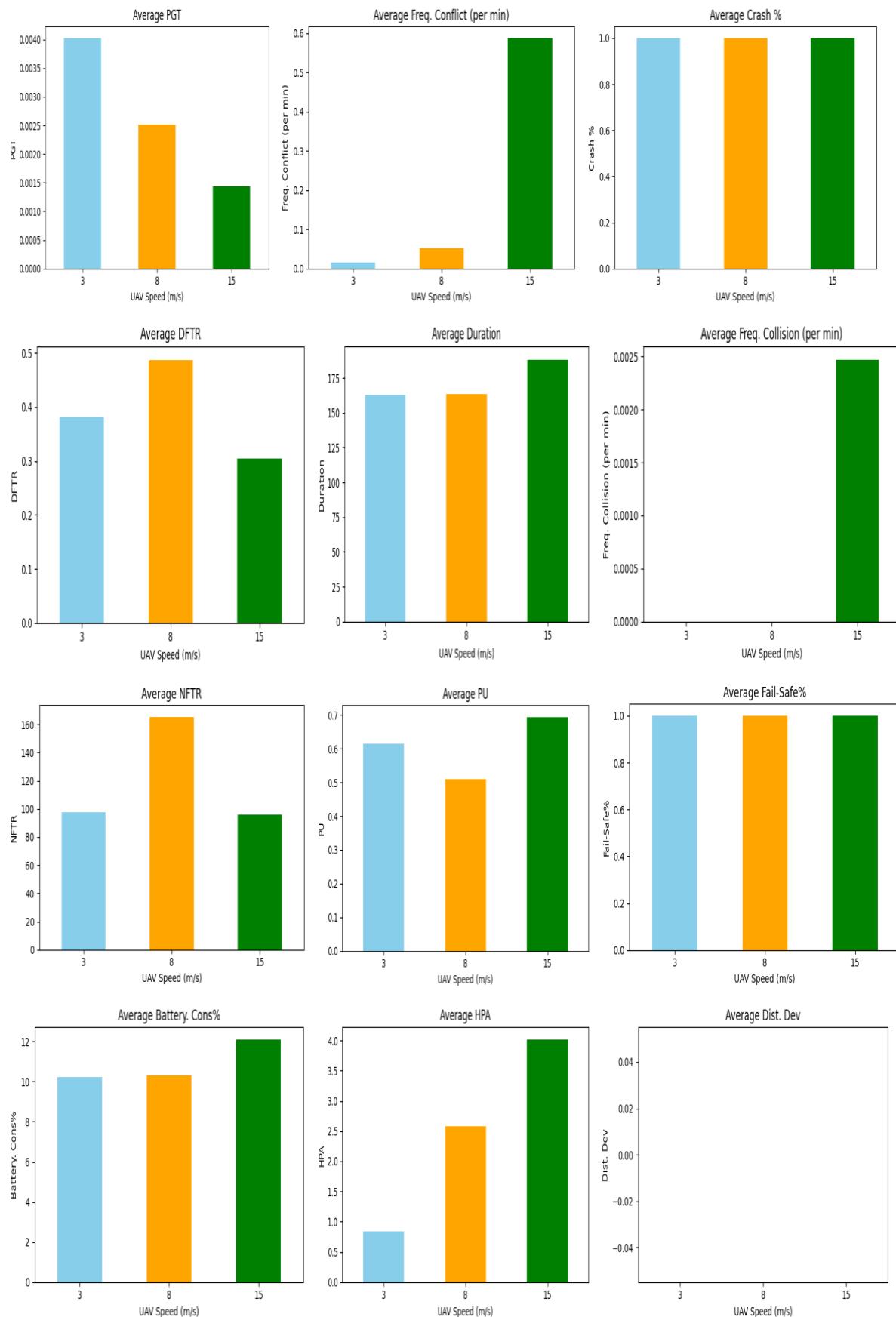


3) Accelerometer faults with near-gale wind:

- Impact of different UAV speeds:

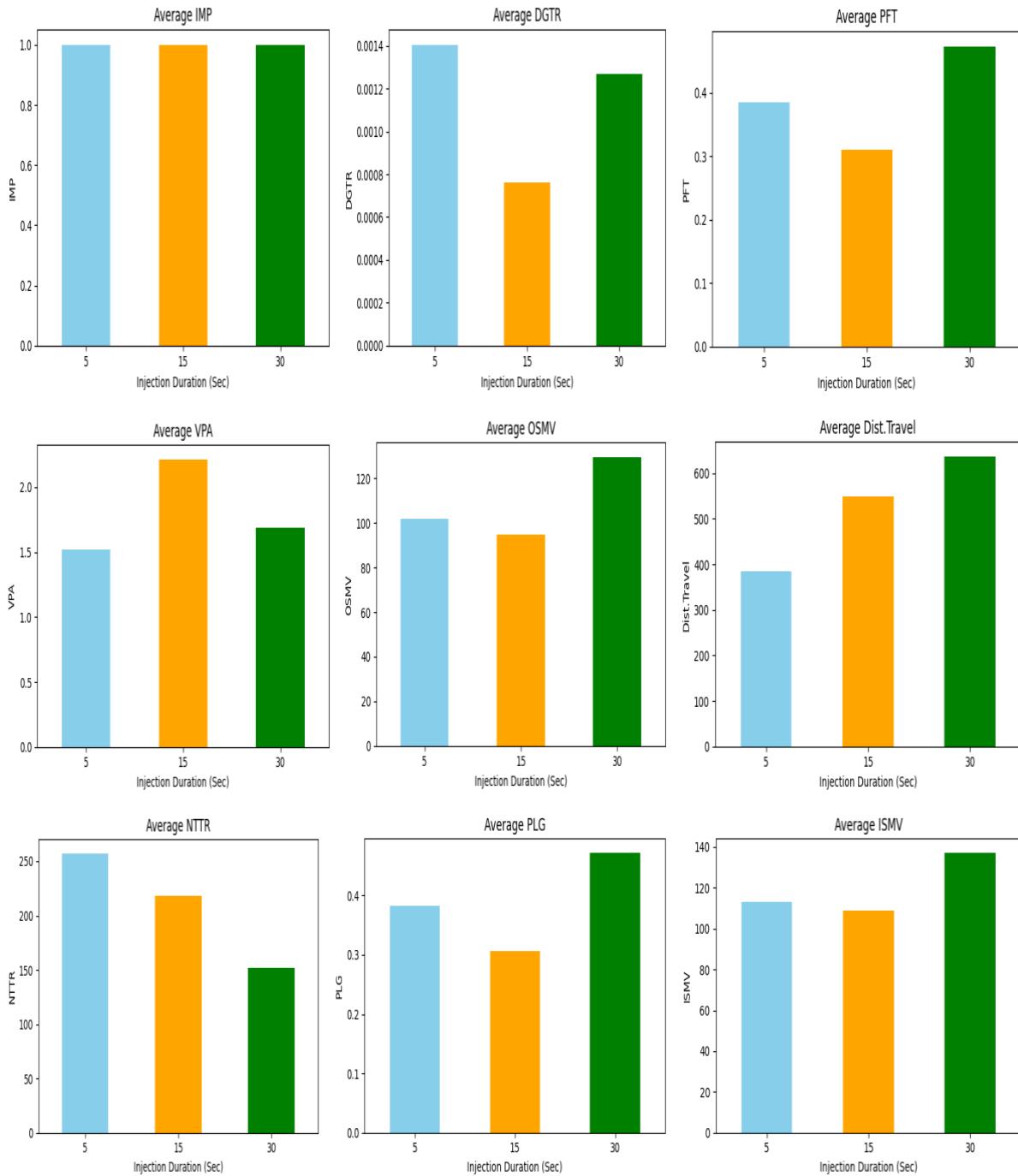


Technical Reports

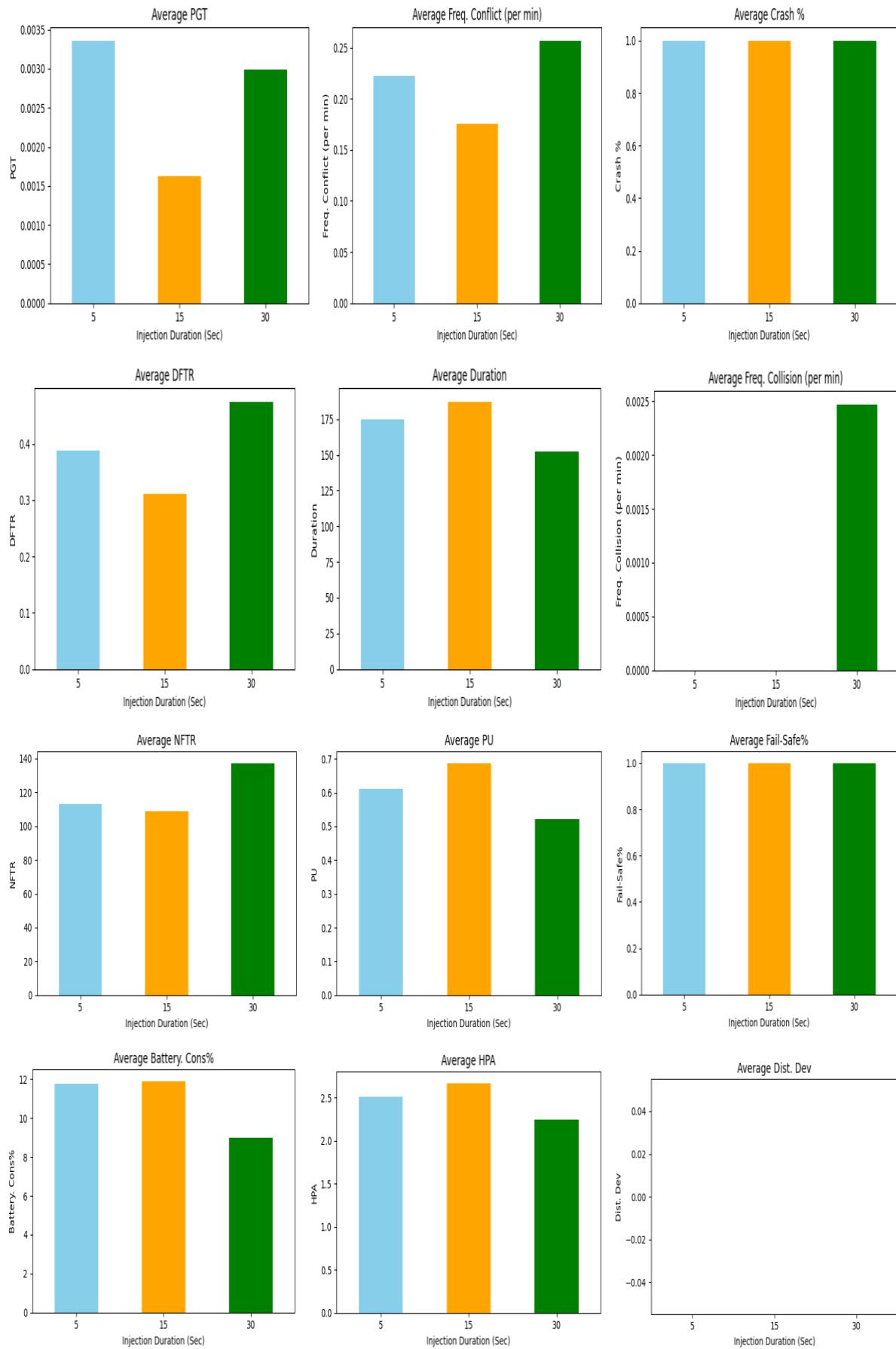


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▪ Impact of different injection durations:

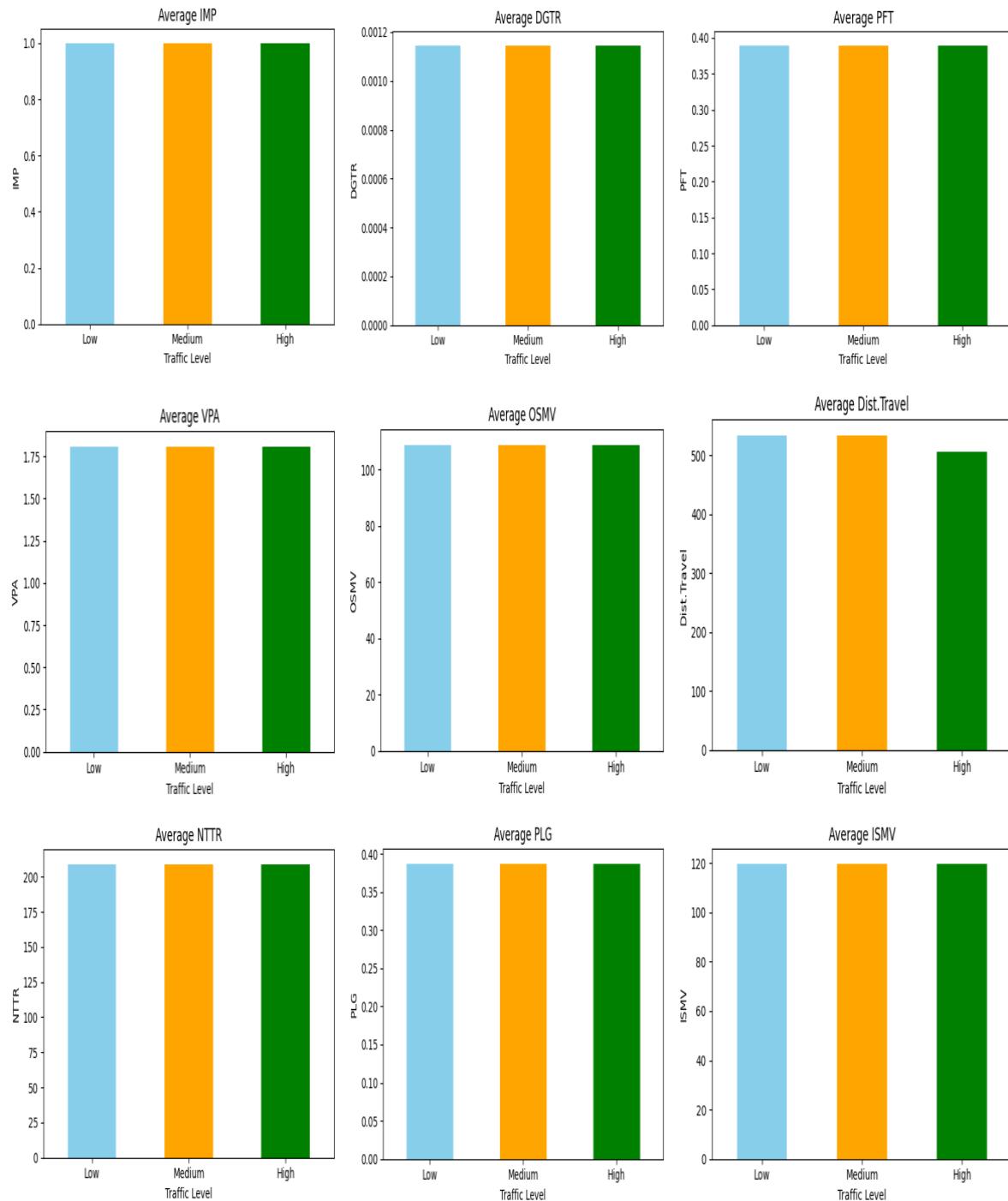


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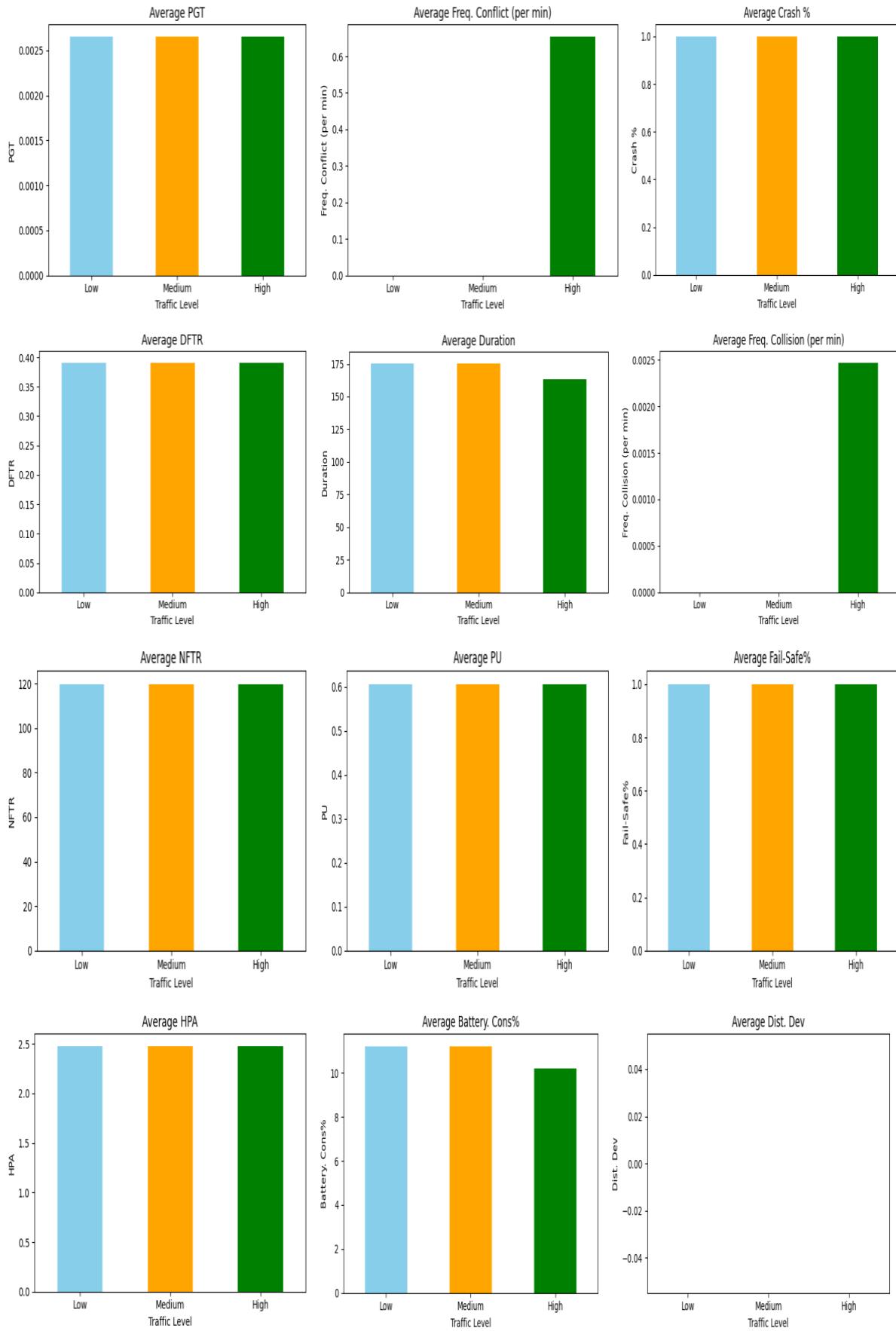


Technical Reports

- **Impact of different traffic levels:**

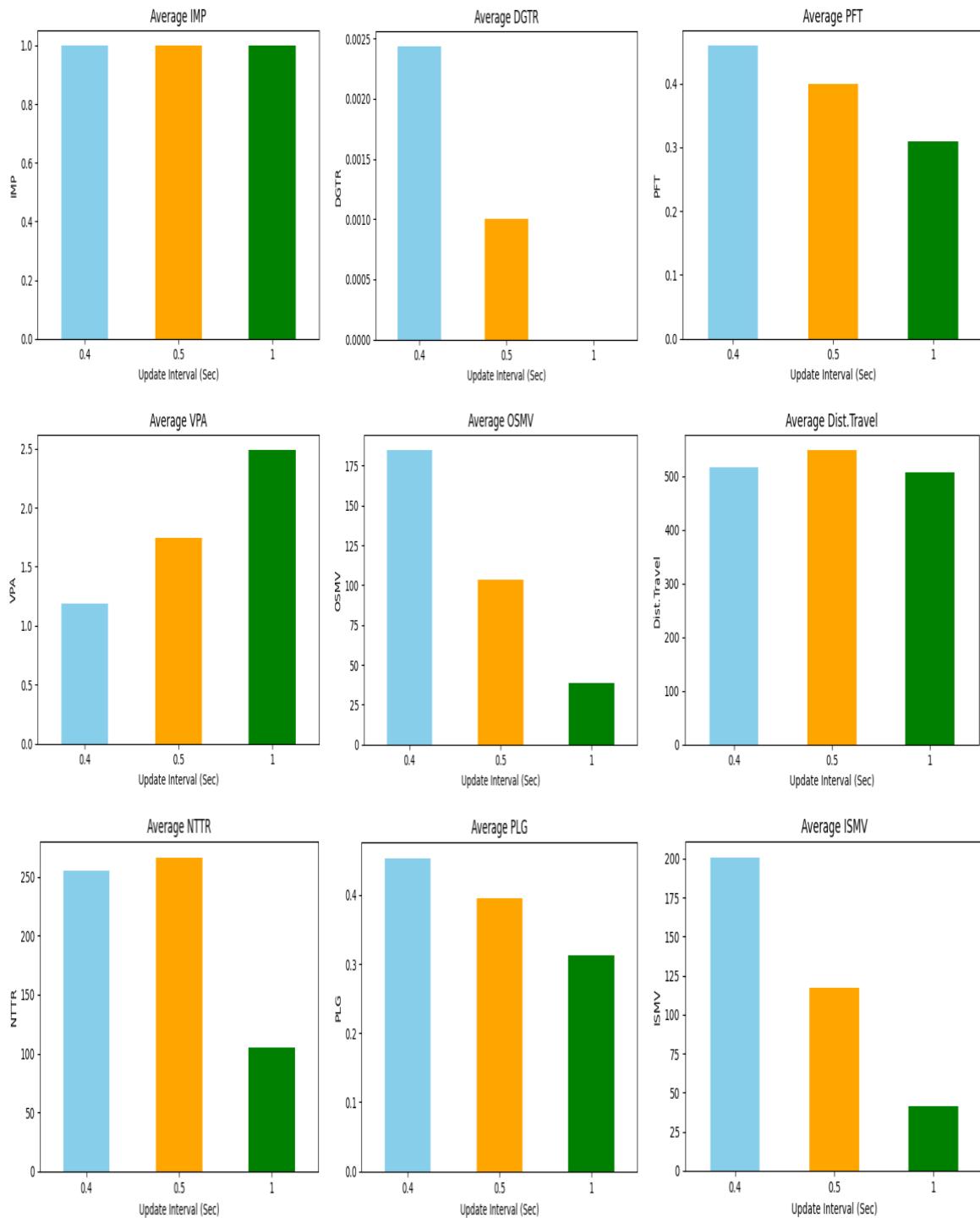


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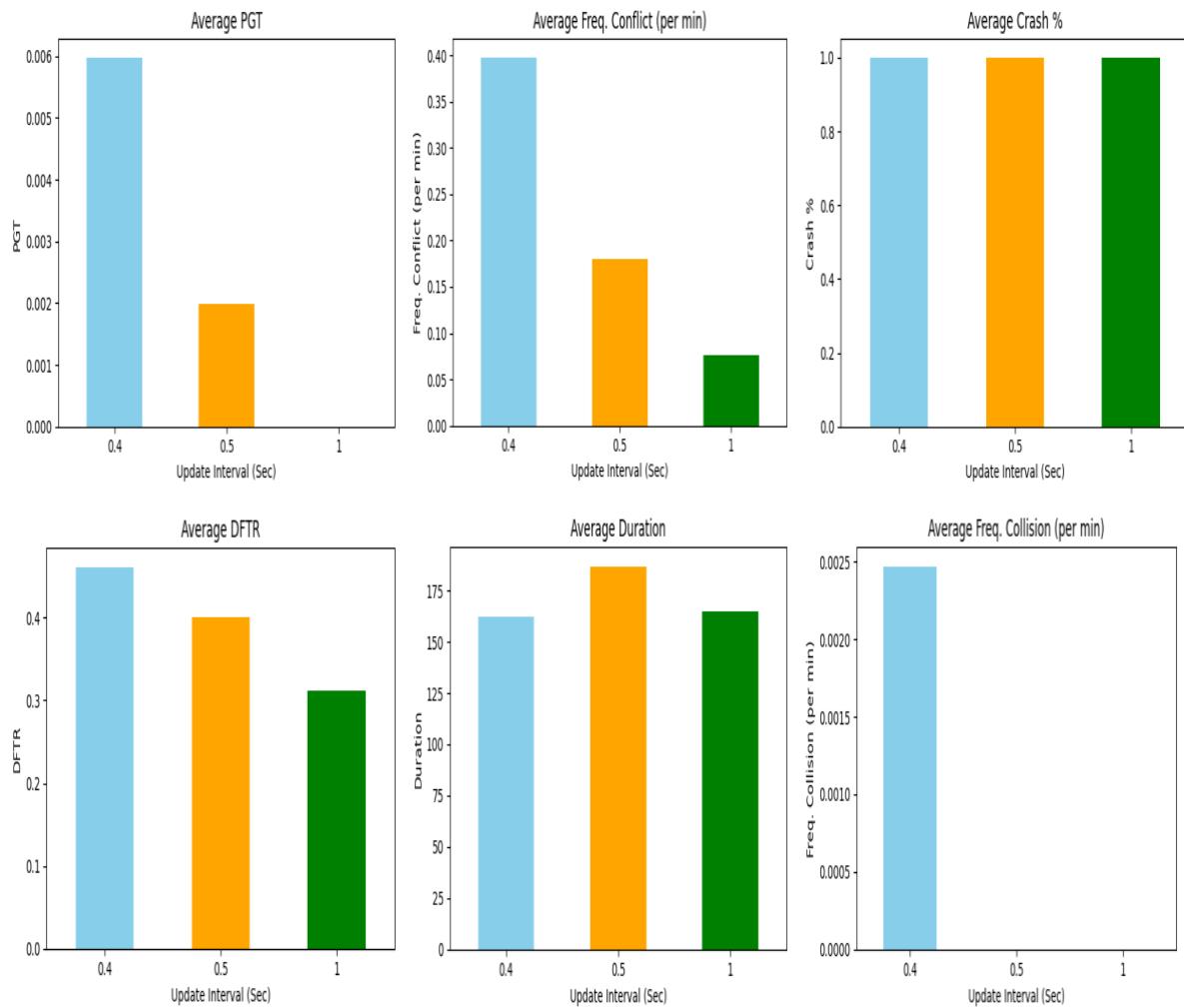


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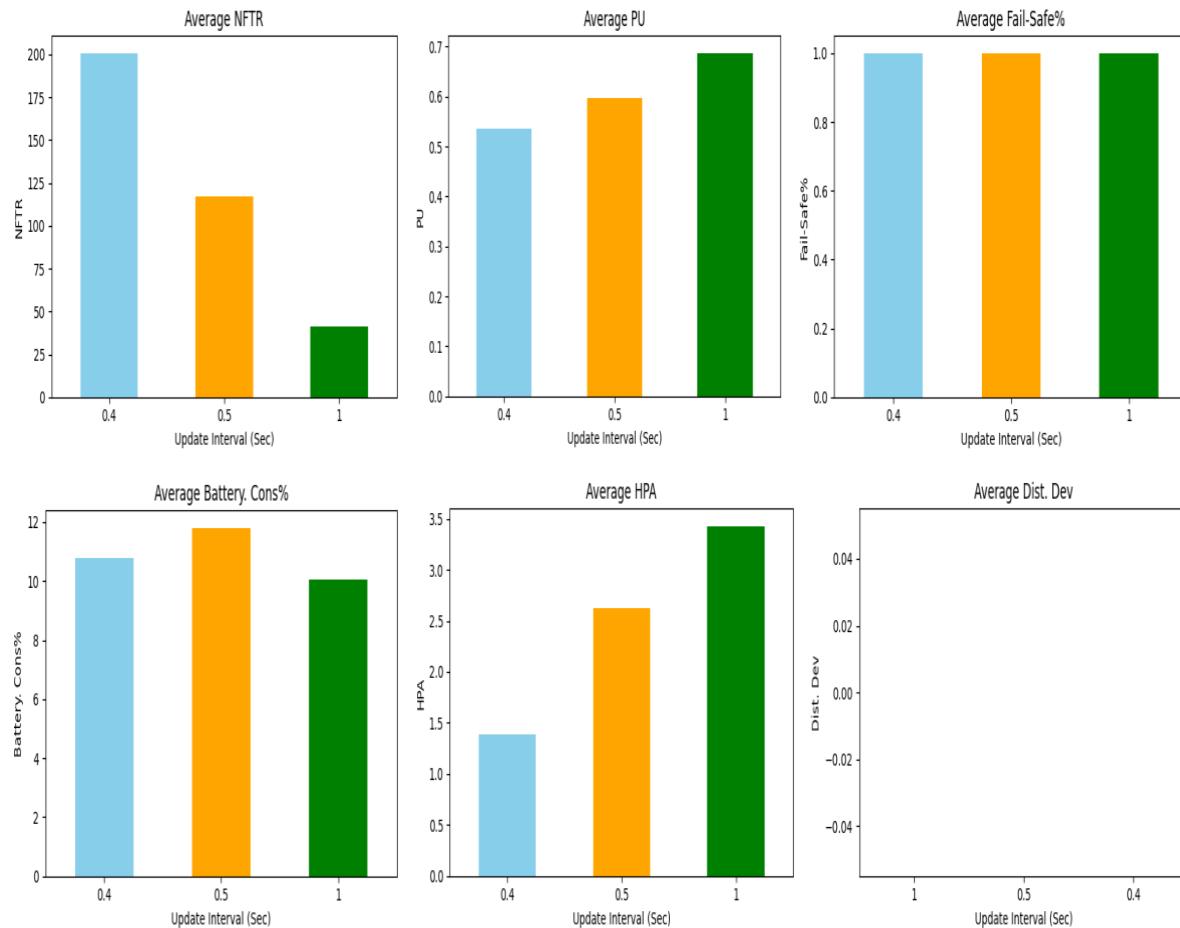
▪ Impact of different update intervals:



Technical Reports

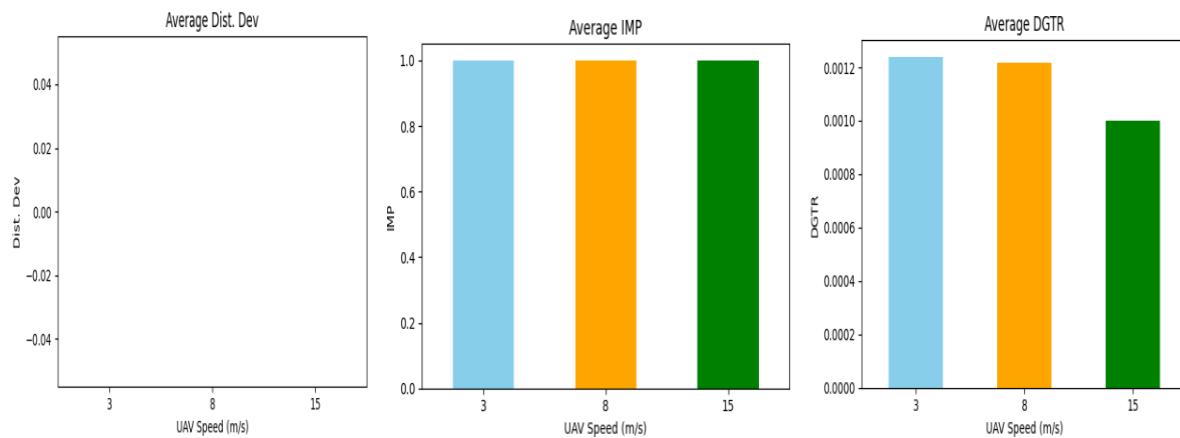


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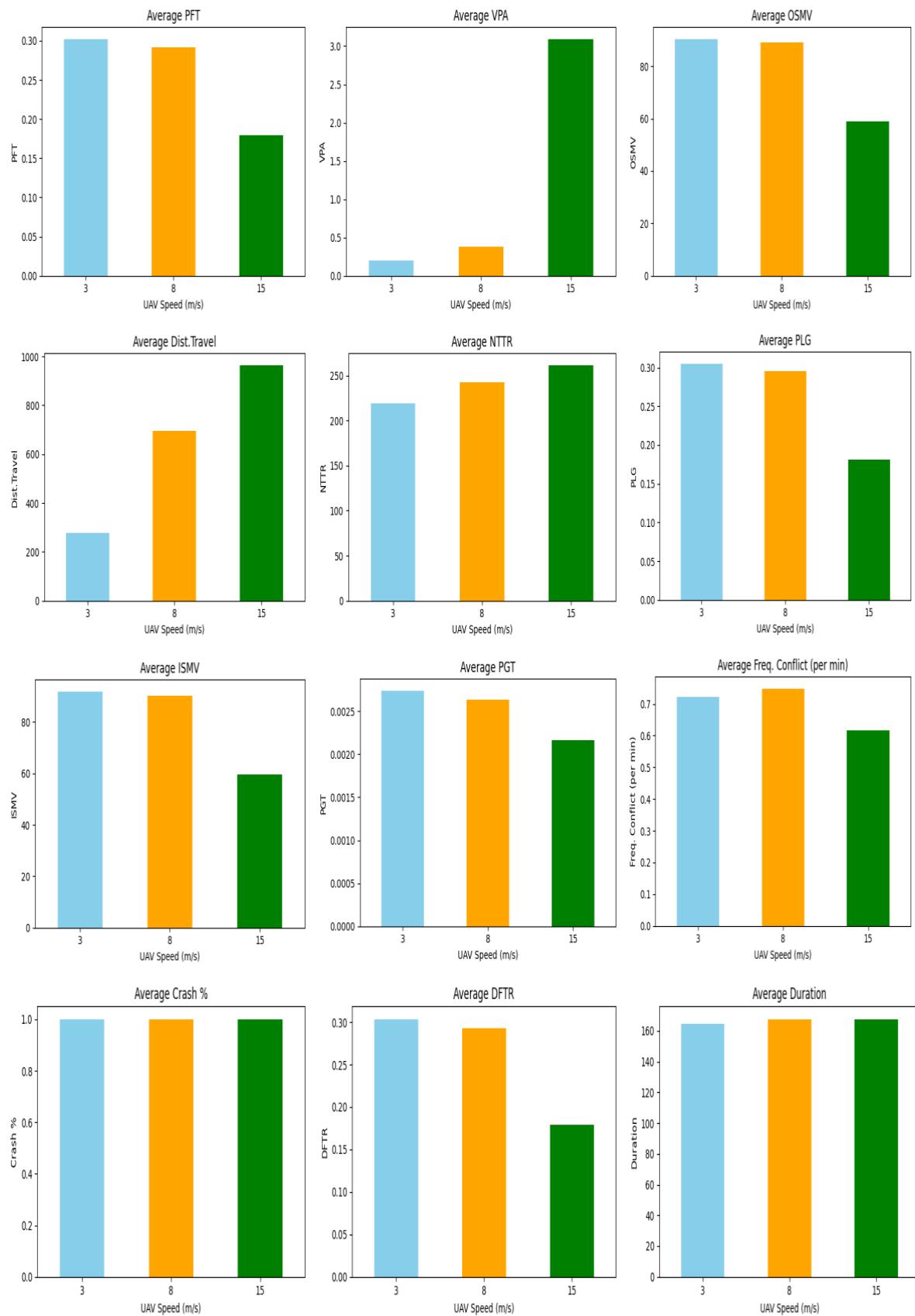


4. Gyroscope with light breeze wind:

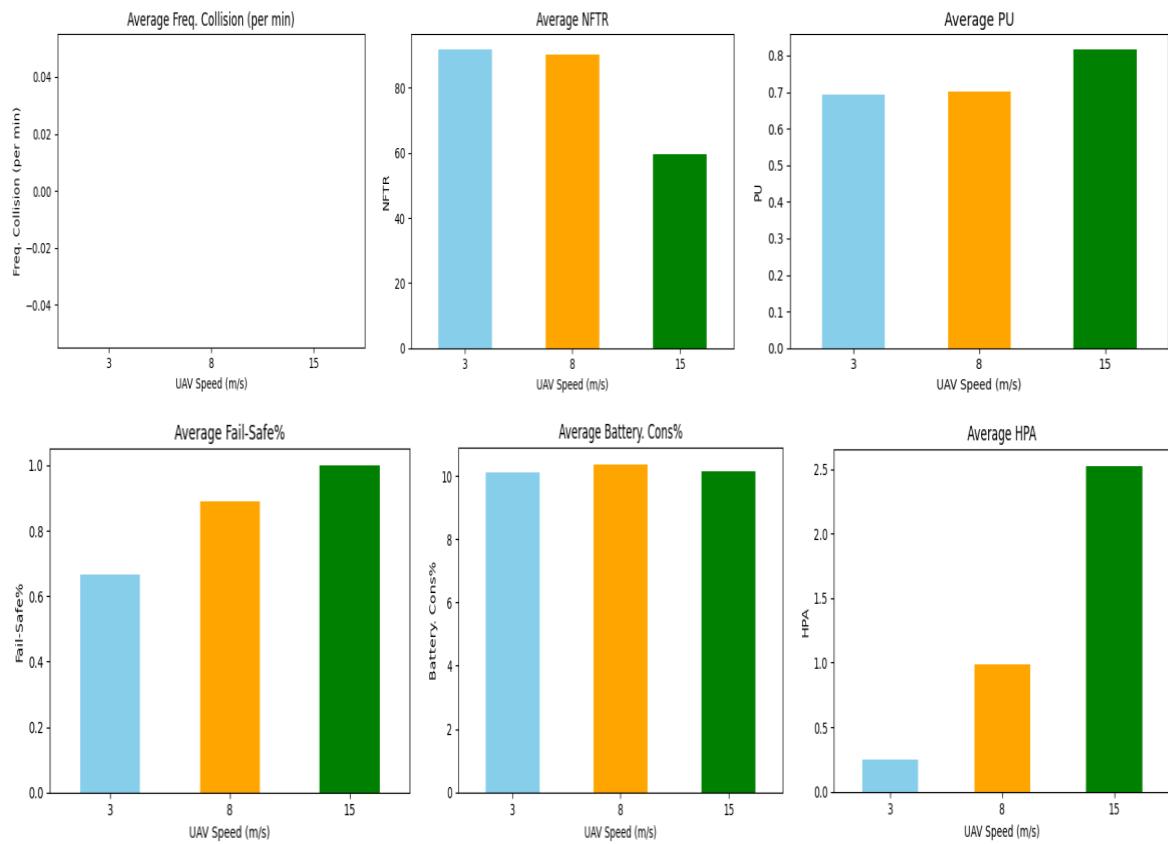
- Impact of the different UAV speeds:



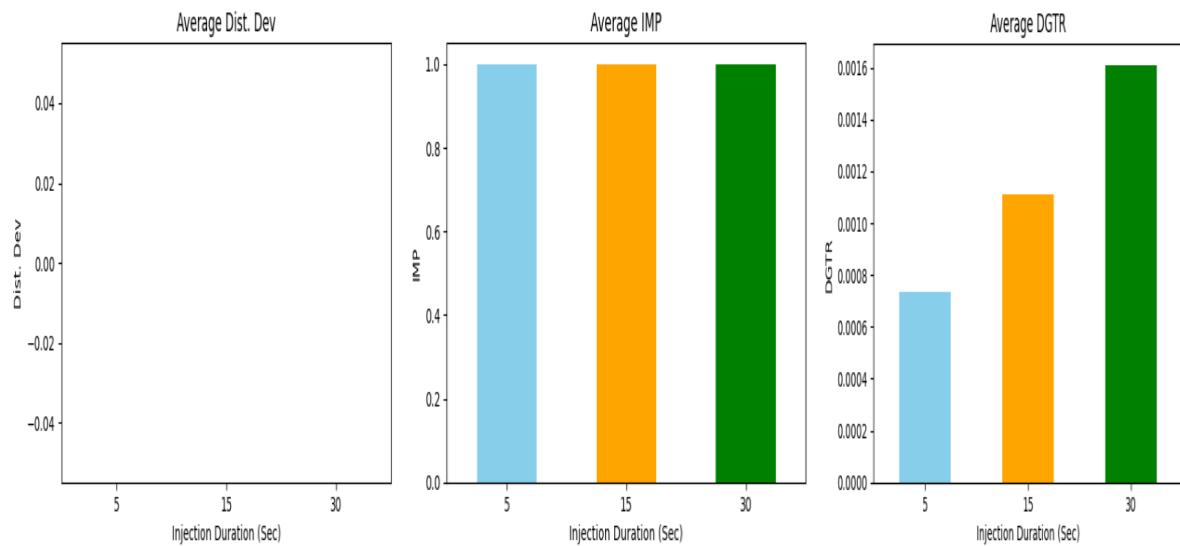
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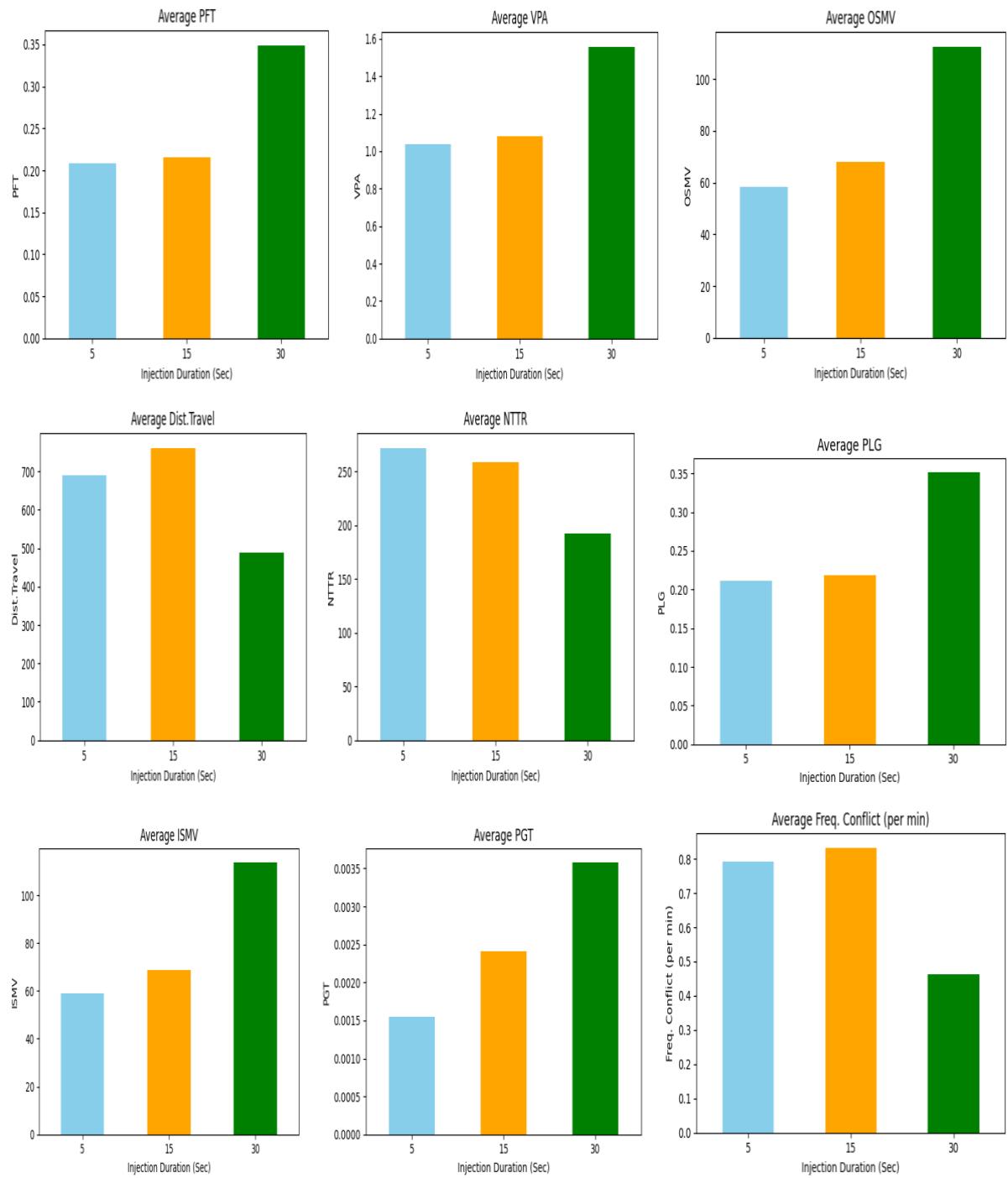
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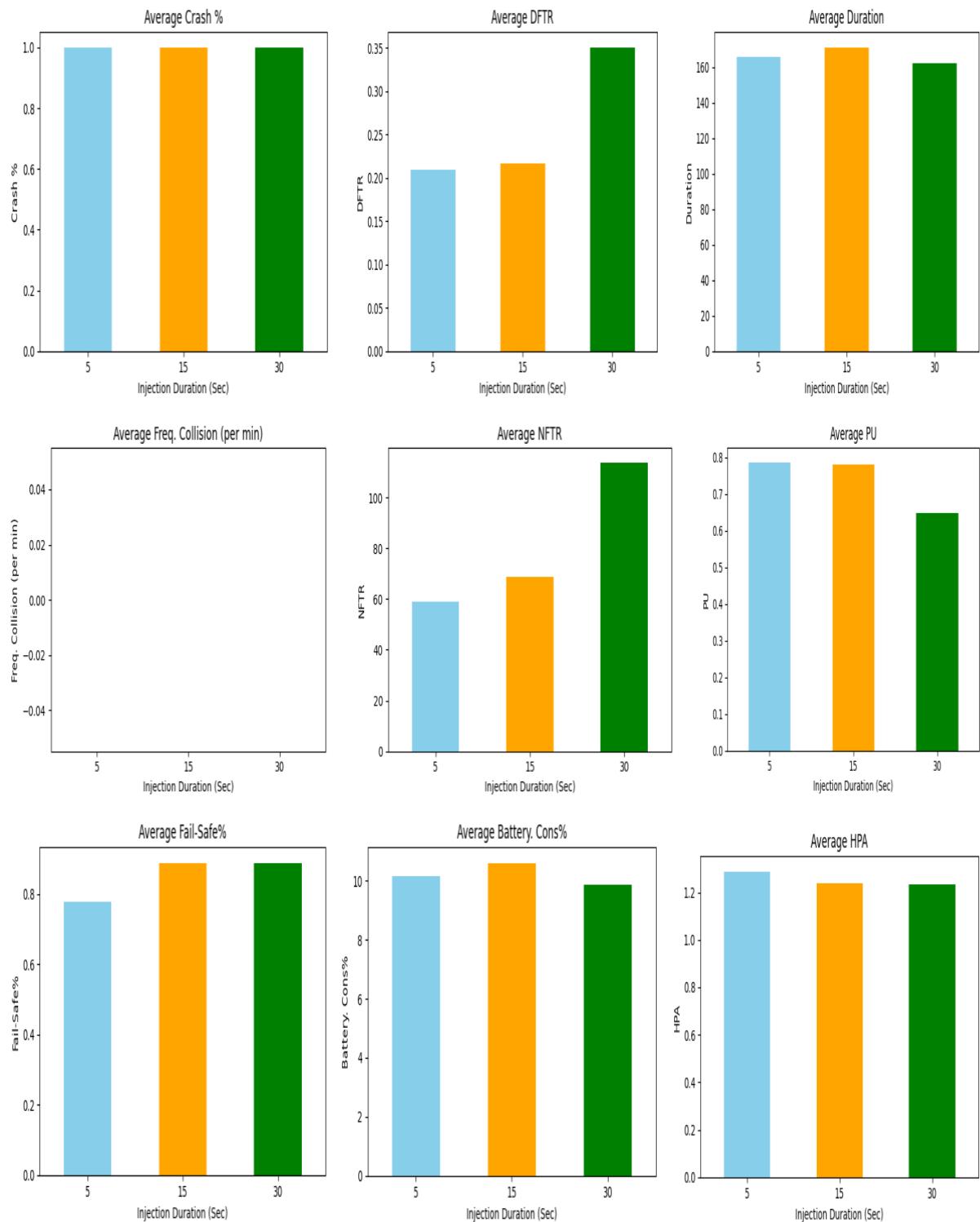
- **Impact of the different injection durations:**



Technical Reports

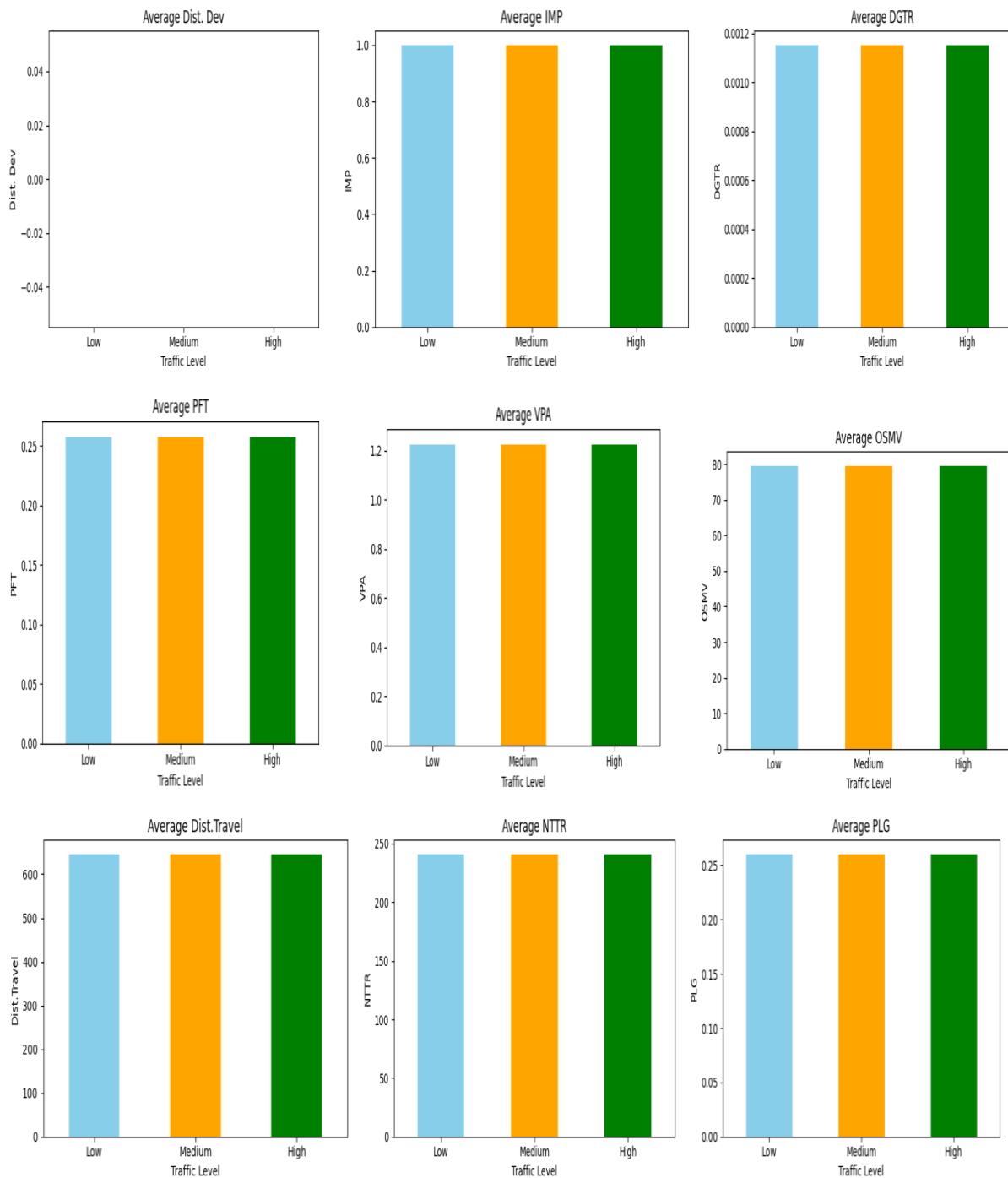


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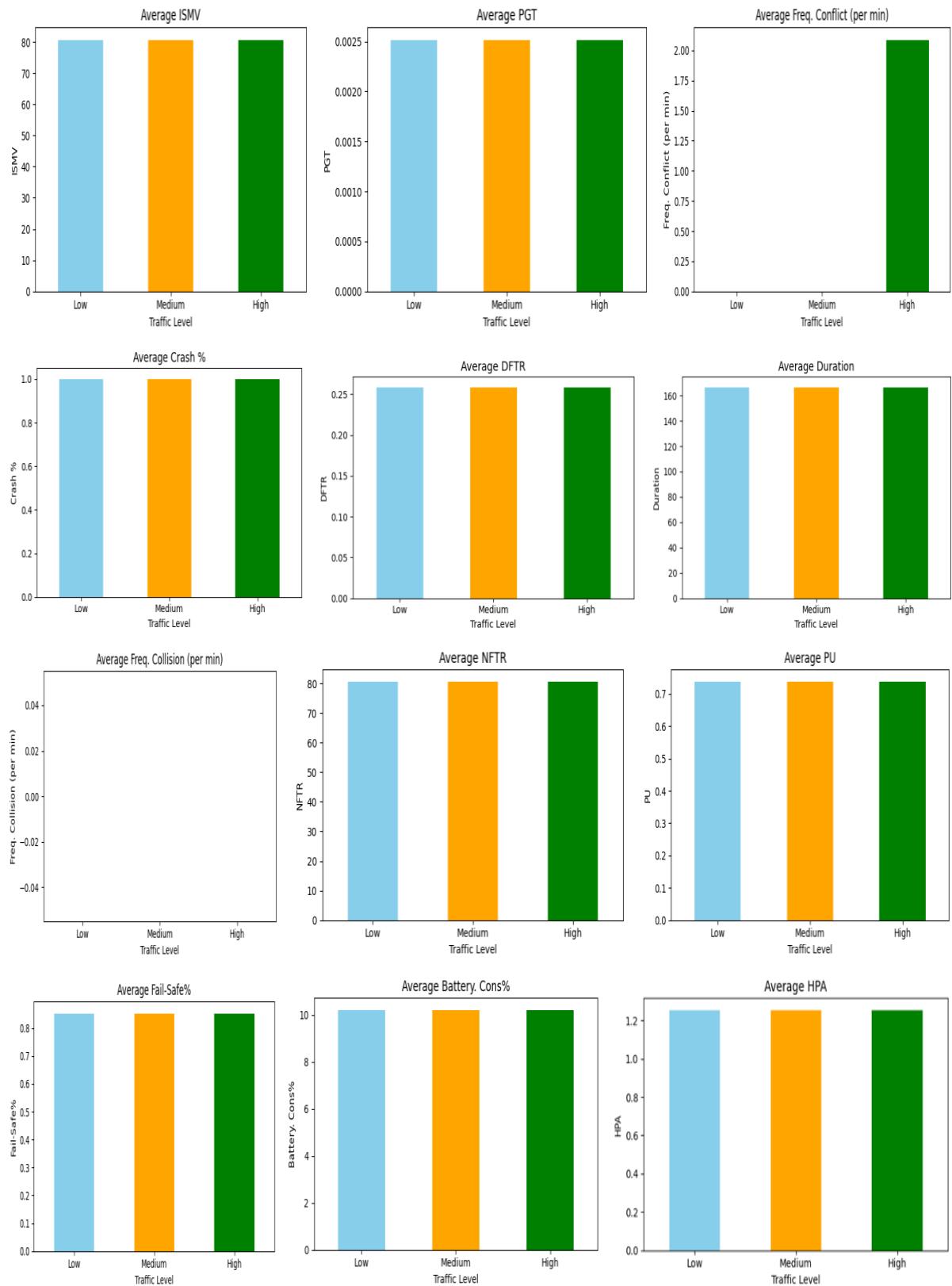


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- **Impact of different traffic levels:**

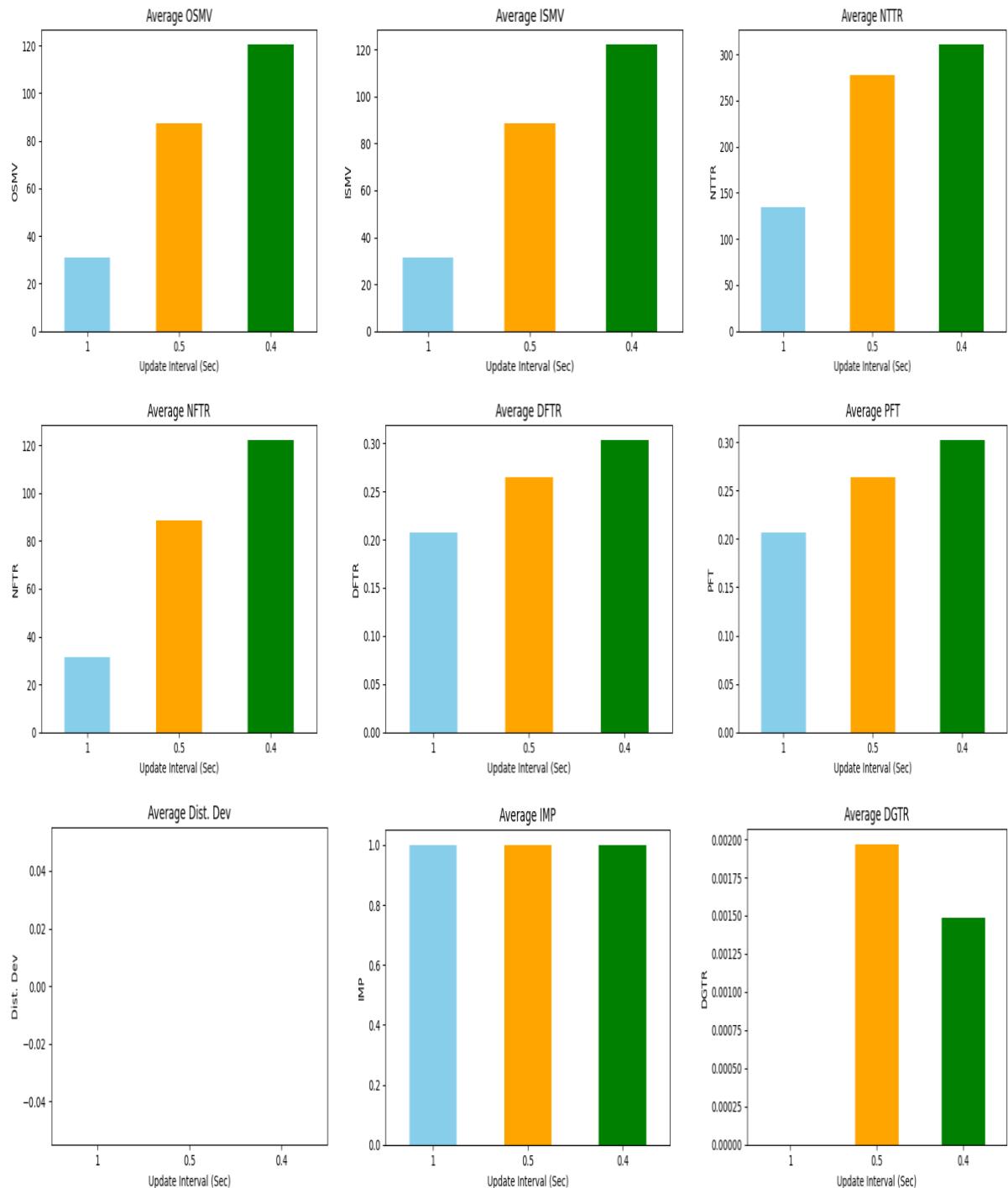


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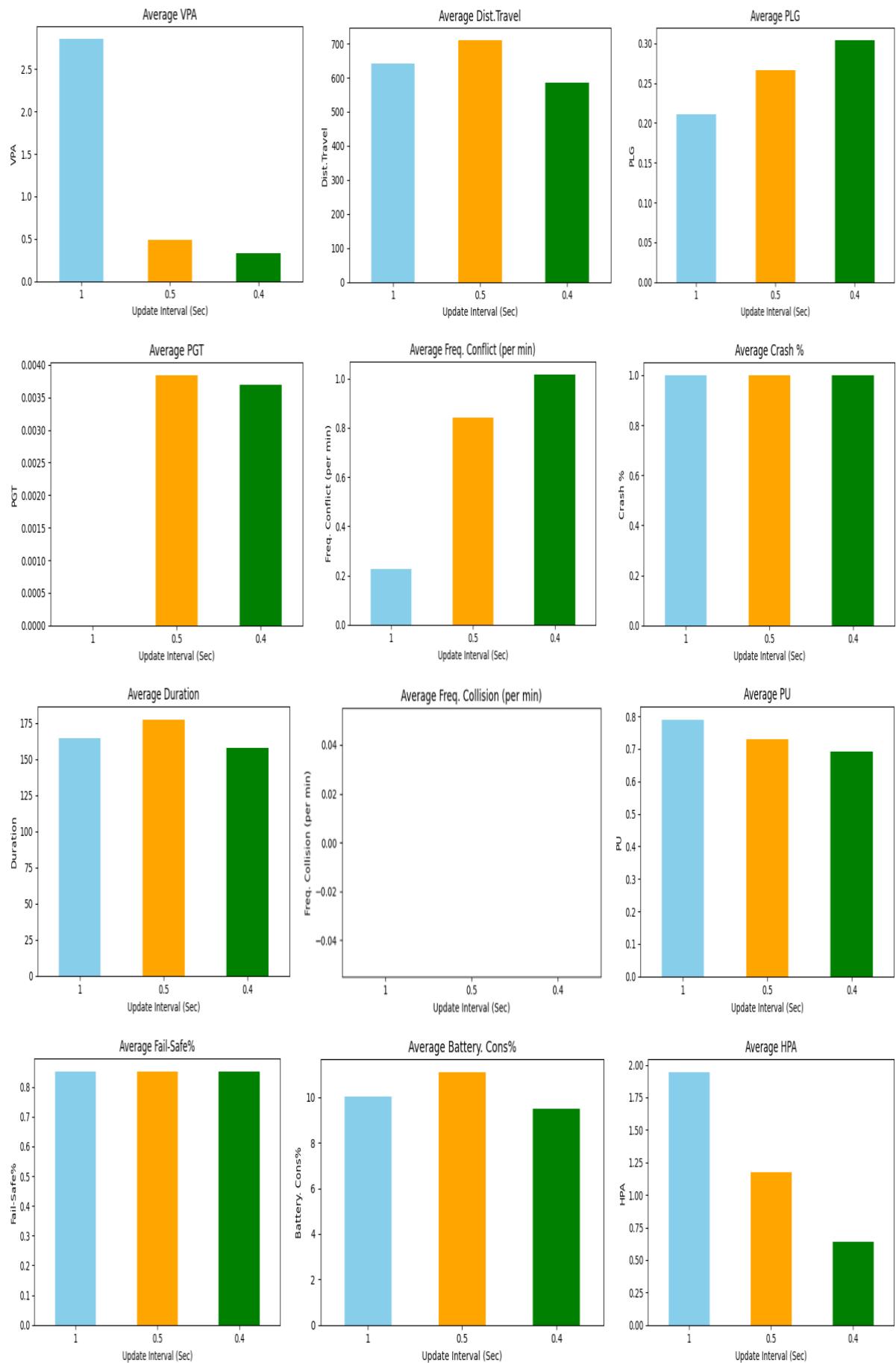


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▪ Impact of different update intervals:

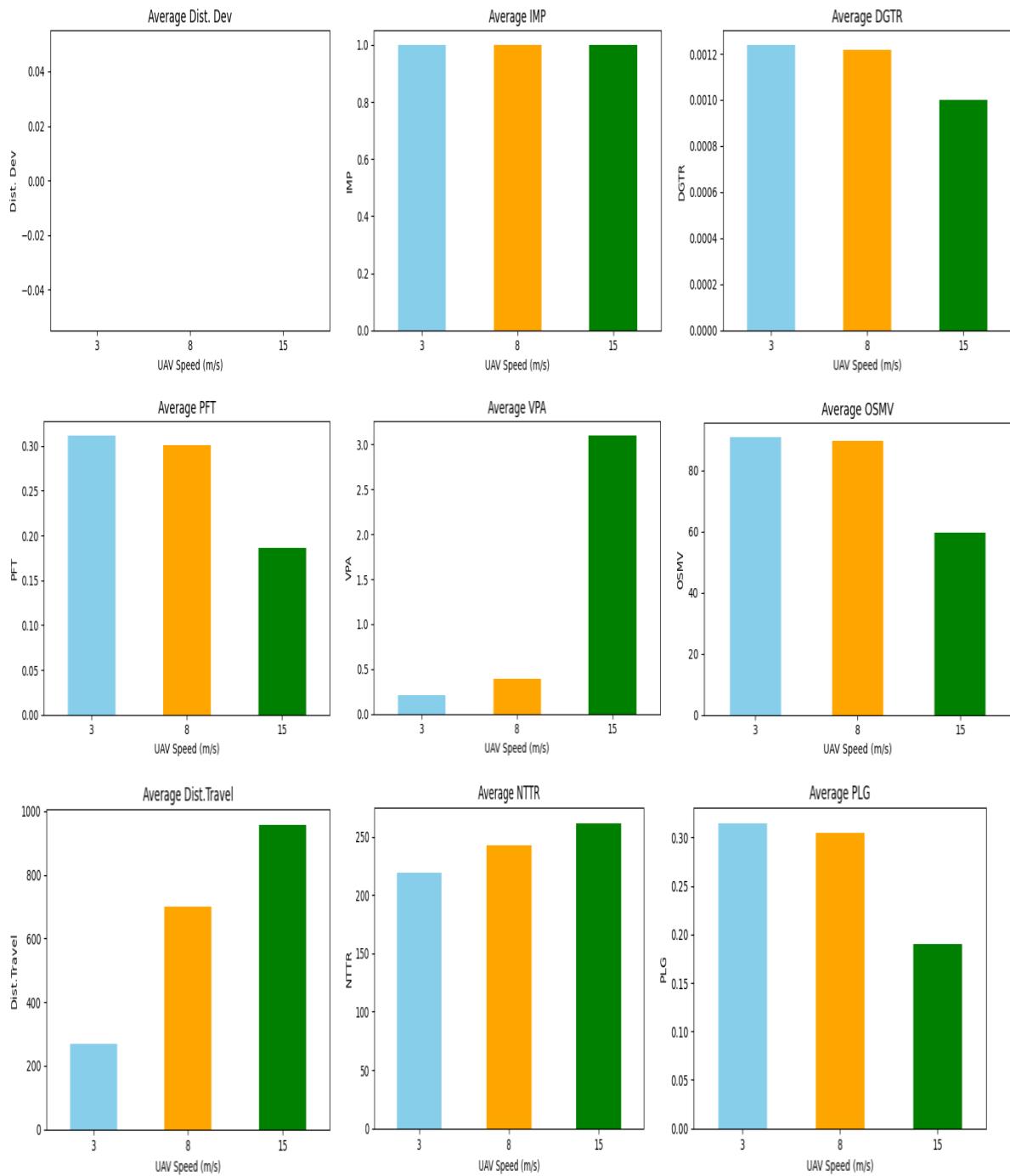


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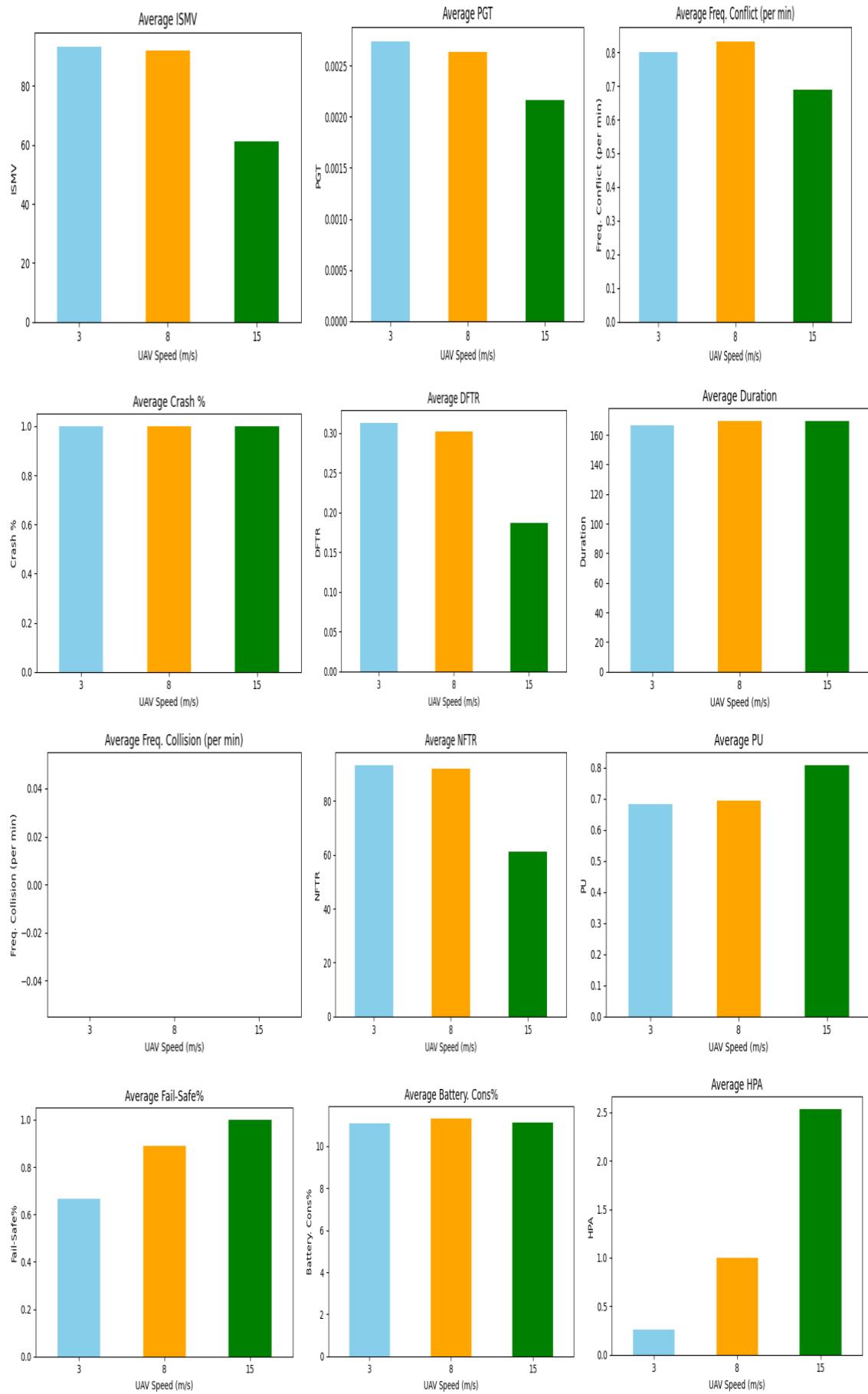


5. Gyroscope with Moderate breeze wind:

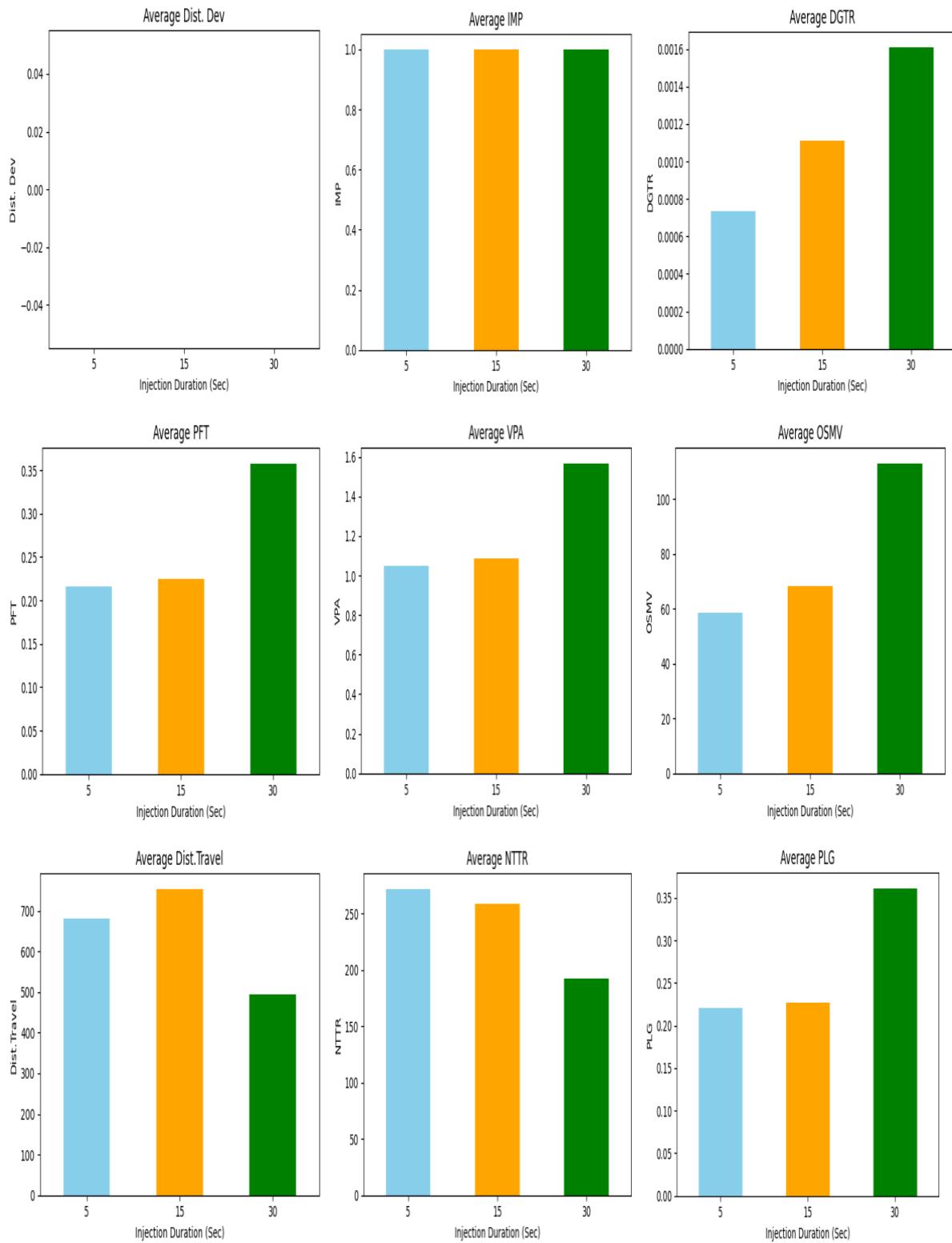
- Impact pf different UAV speeds:



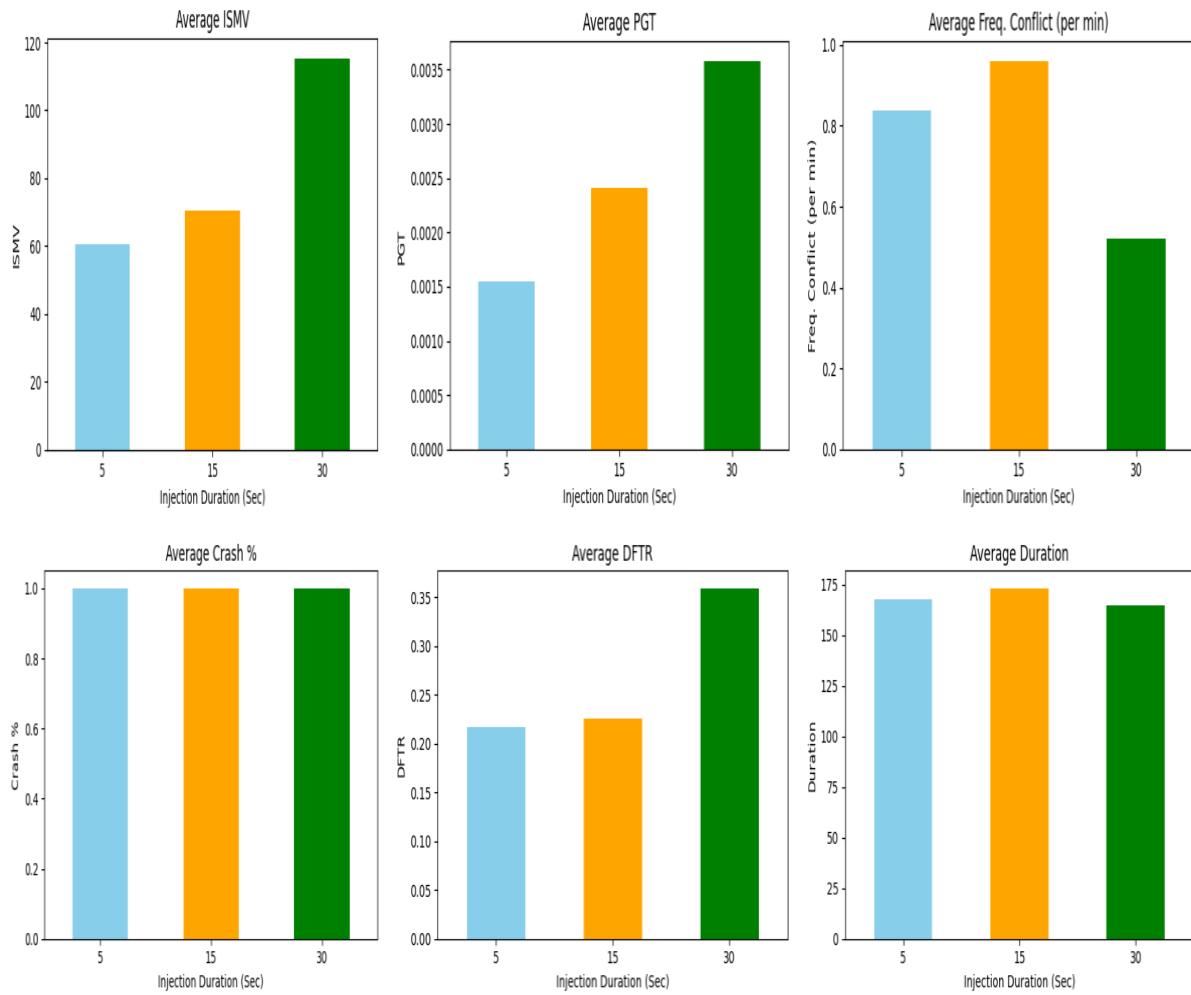
Technical Reports



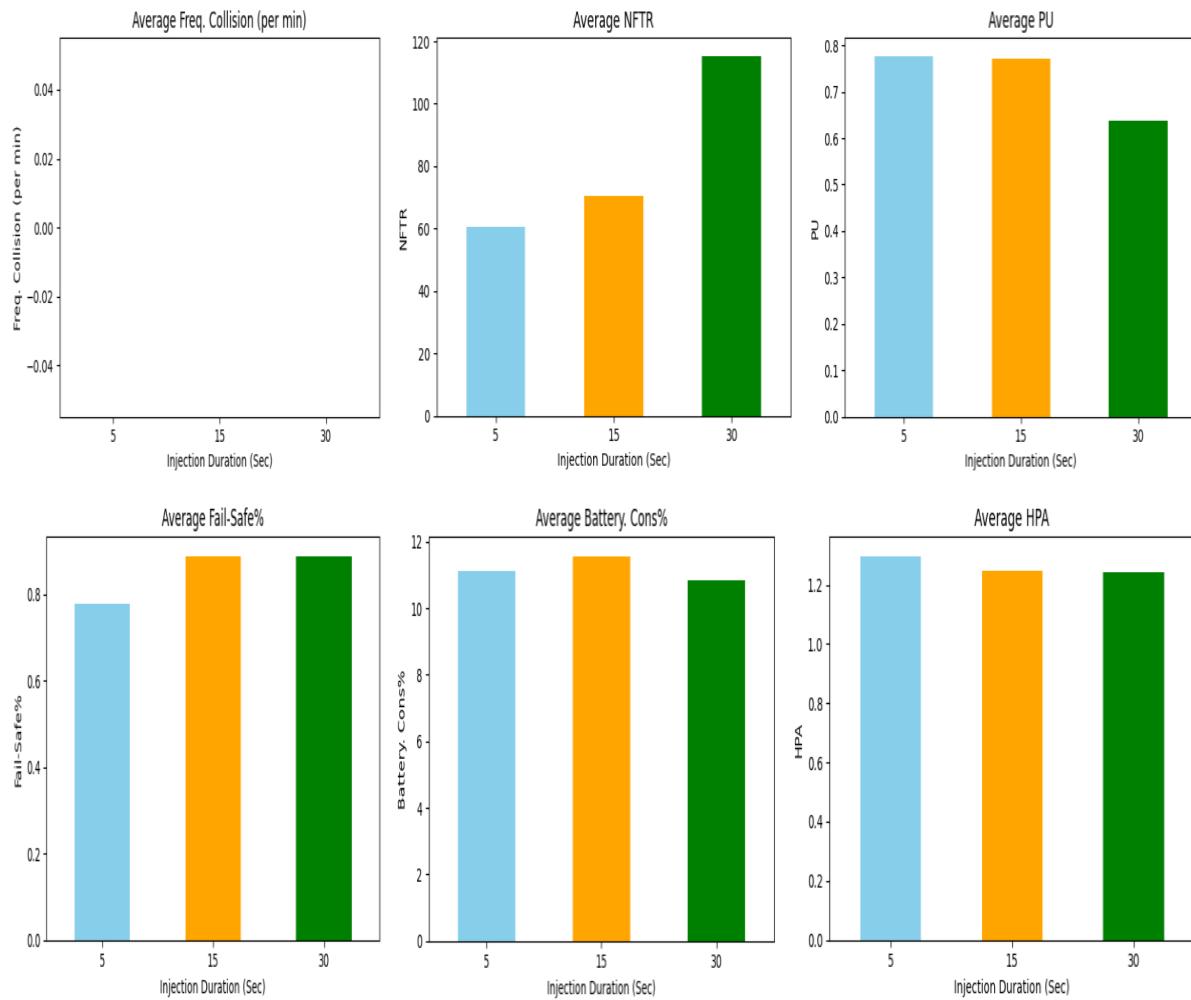
- **Impact of the different Injection durations:**



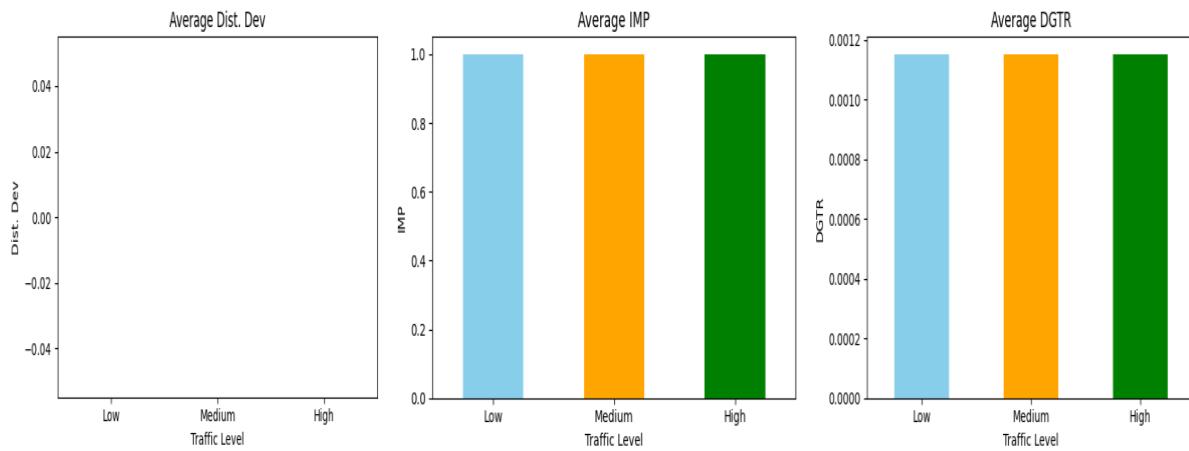
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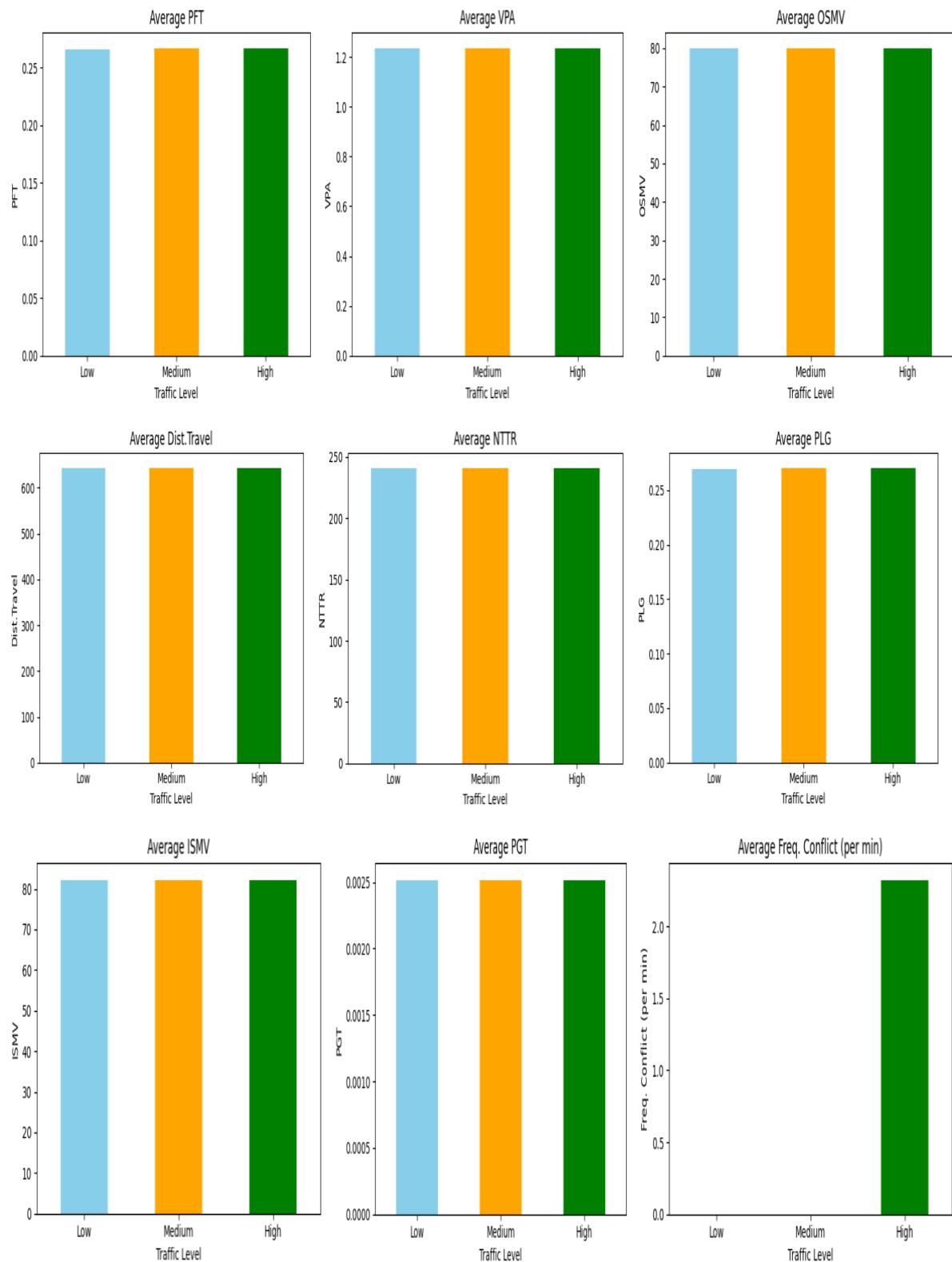
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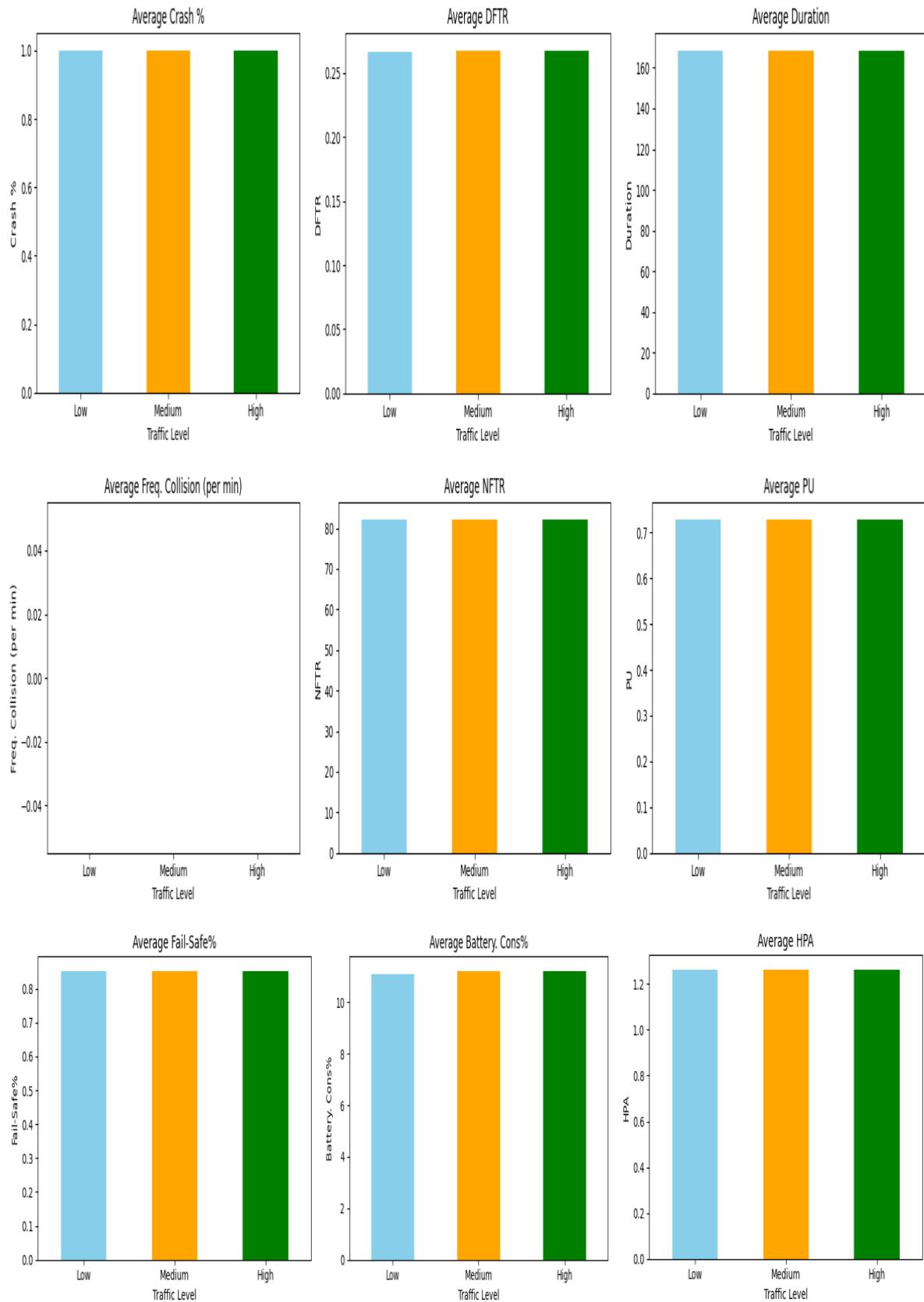
- **Impact of different Traffic Levels:**



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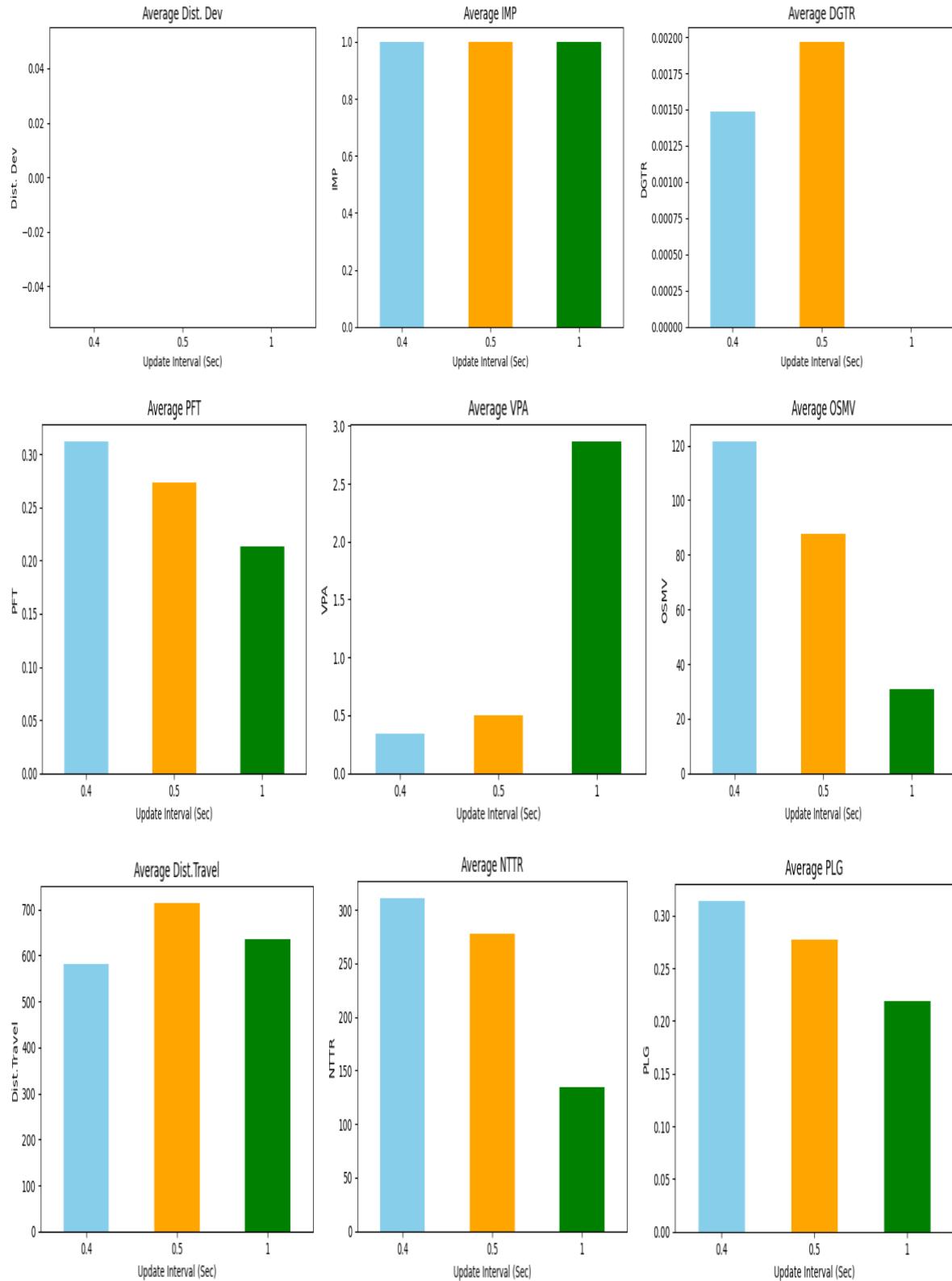


Technical Reports

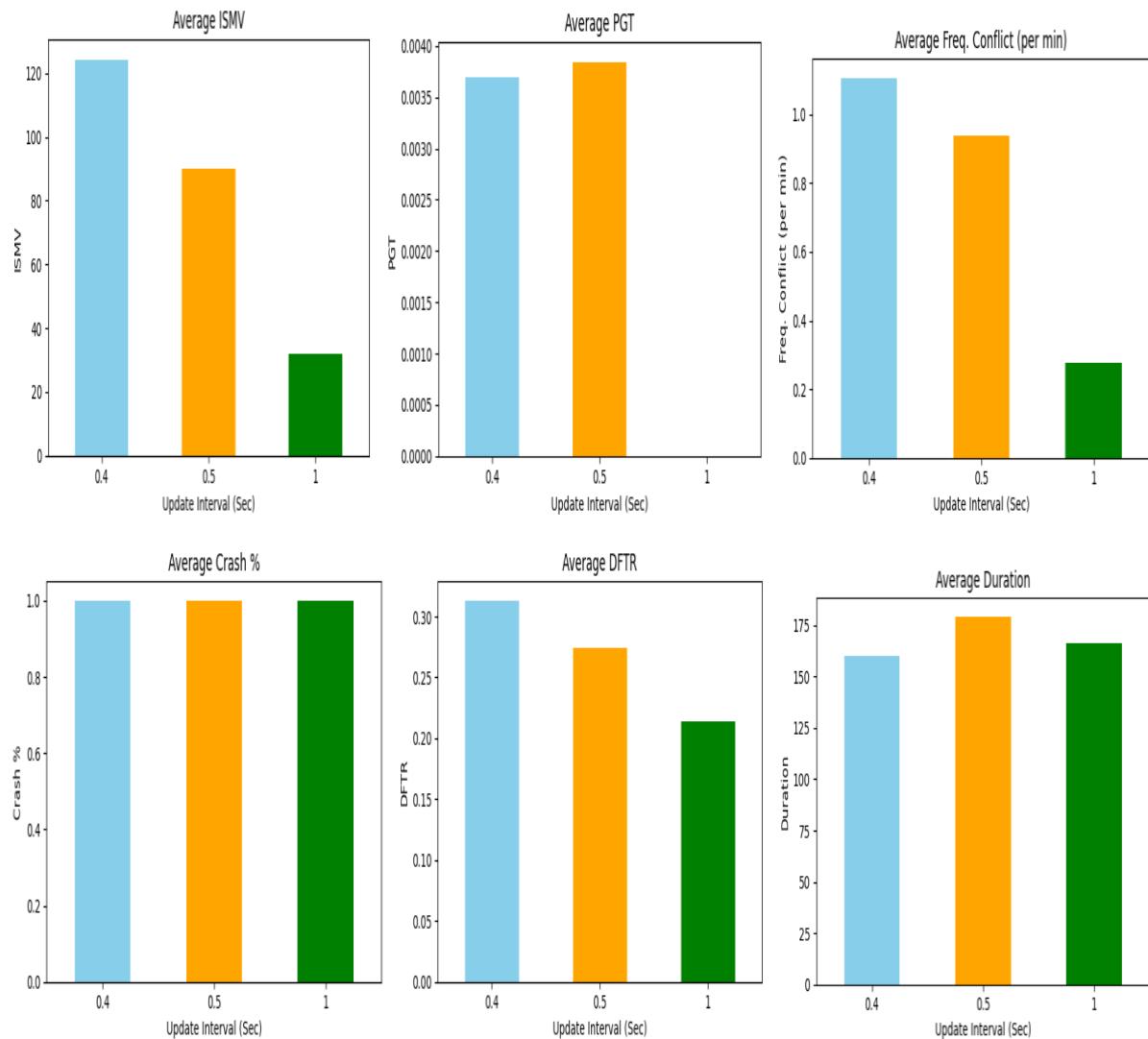


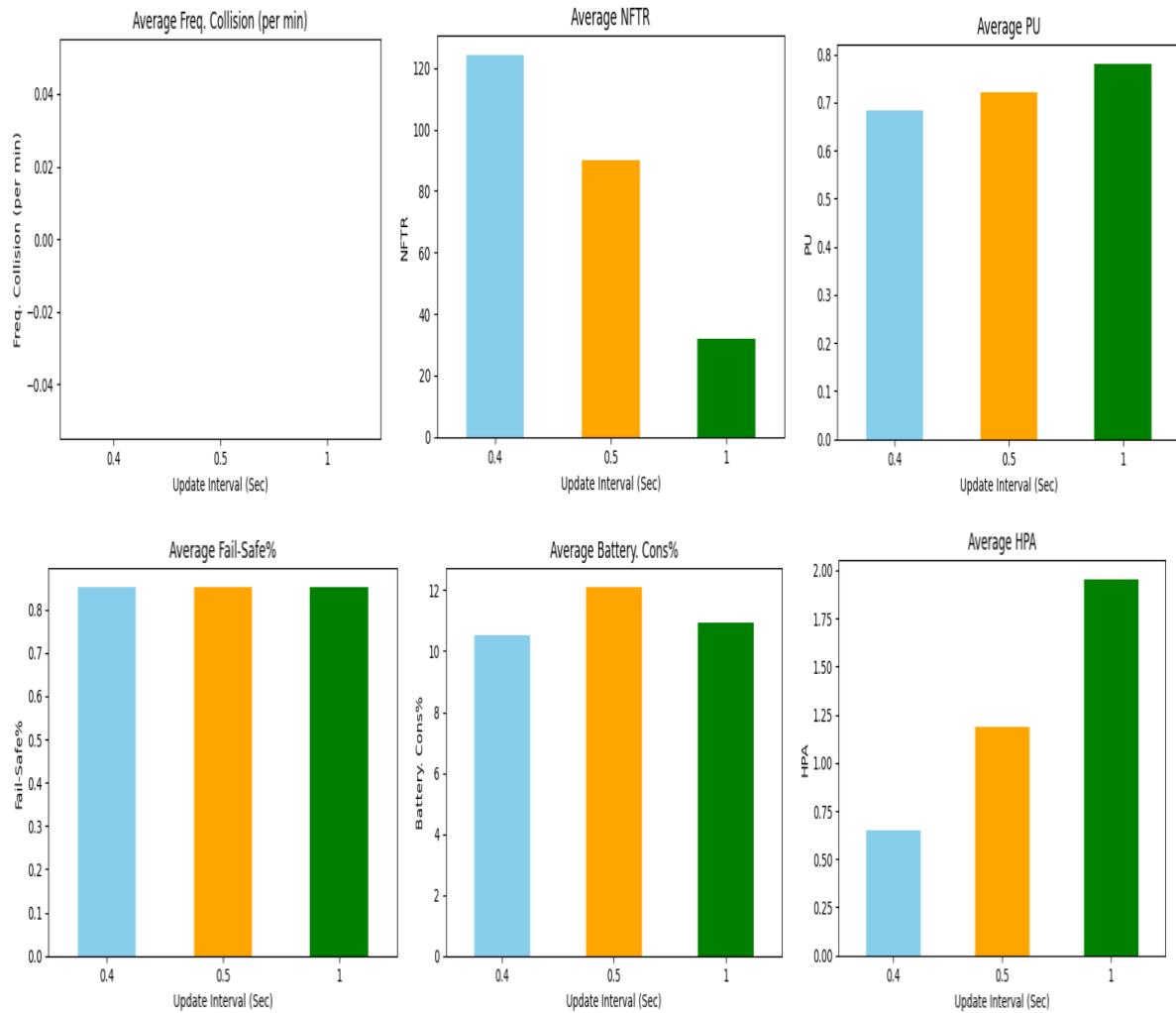
Technical Reports

▪ Impact of Different update Intervals:



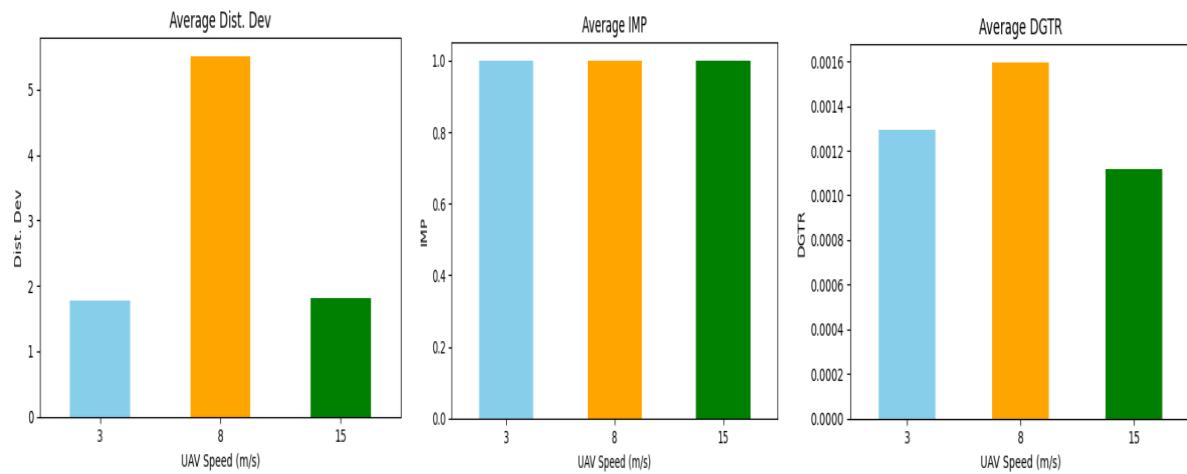
Technical Reports



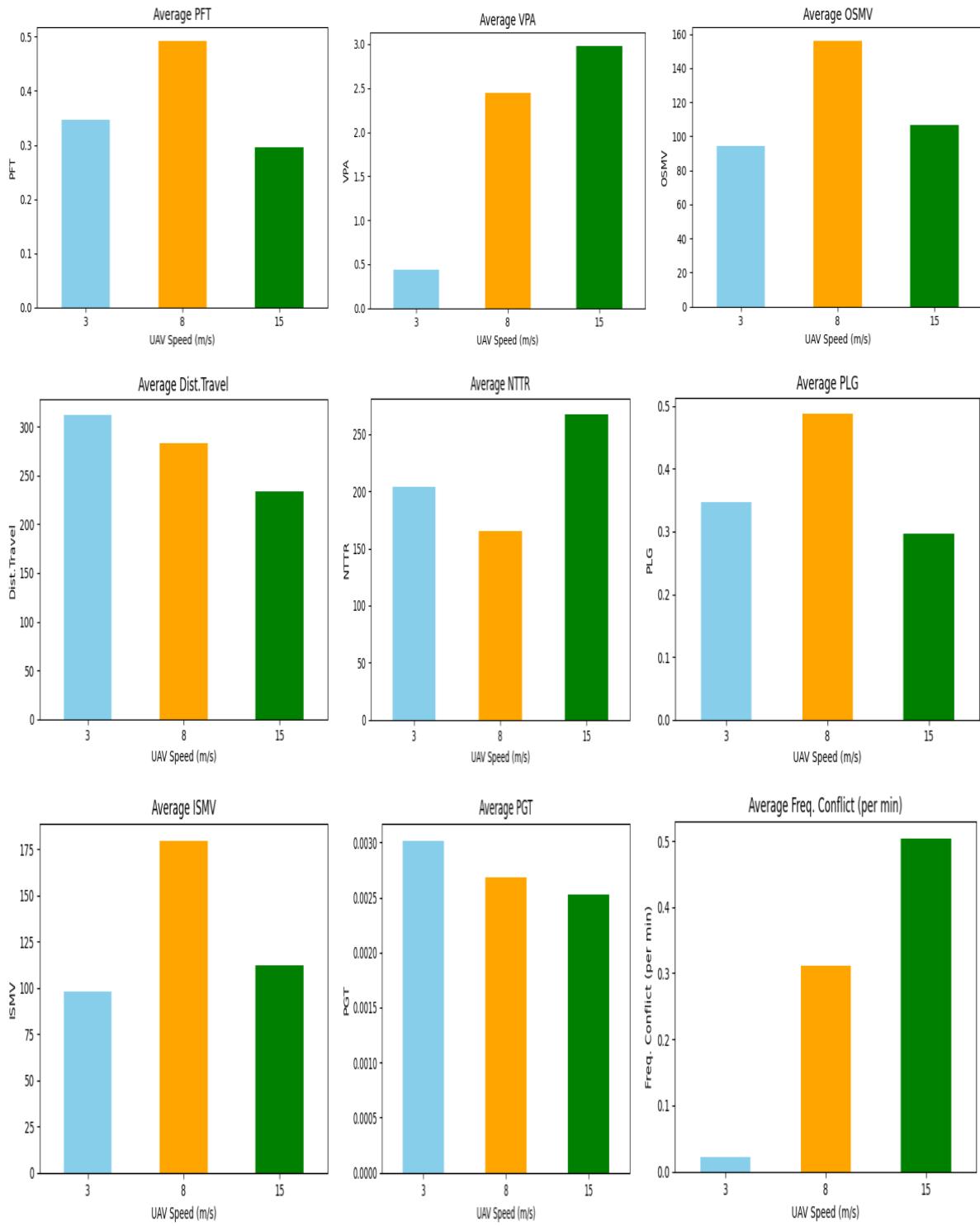


6. Gyroscope with near-gale wind:

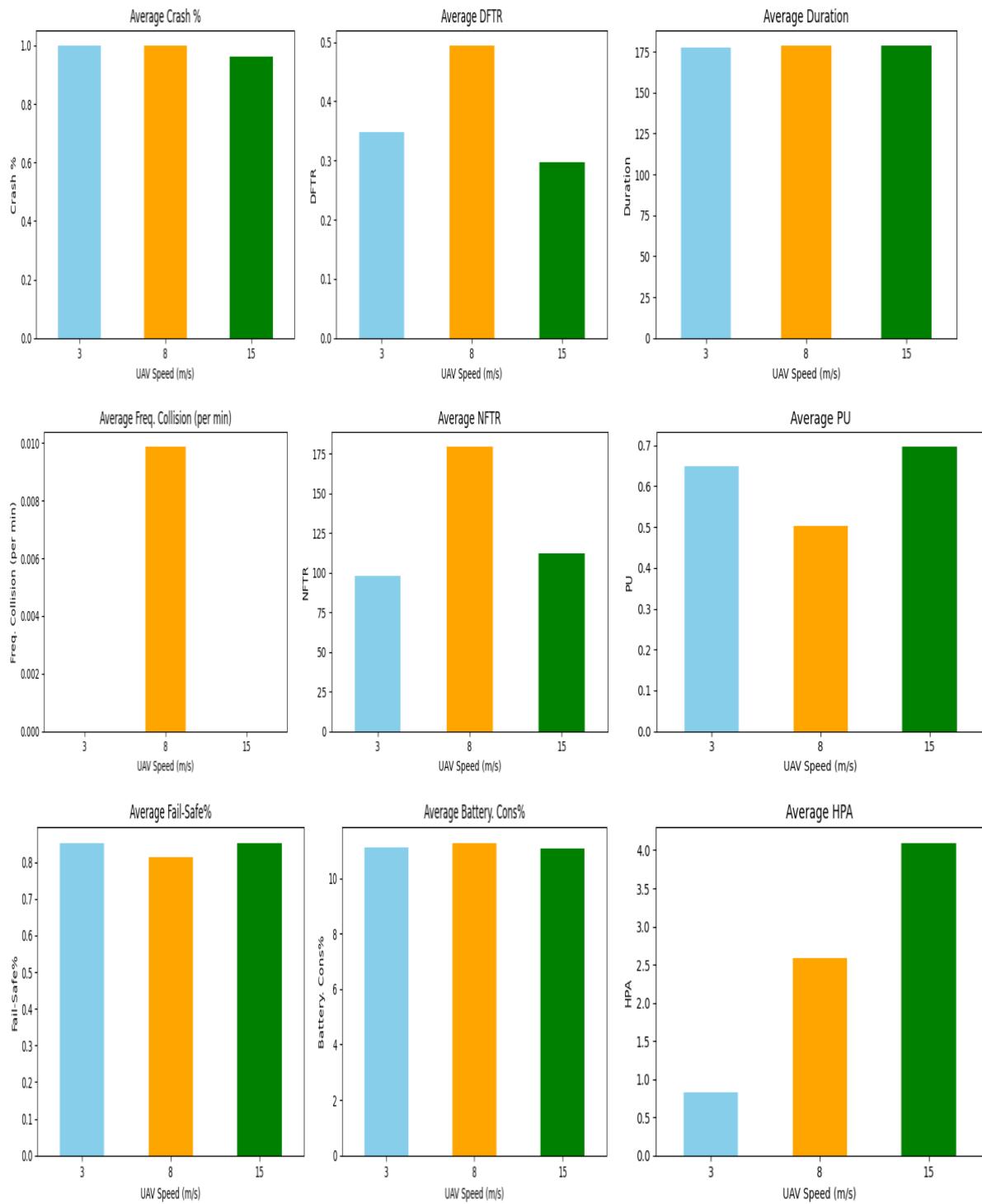
- Impact of different UAV speeds:



Technical Reports

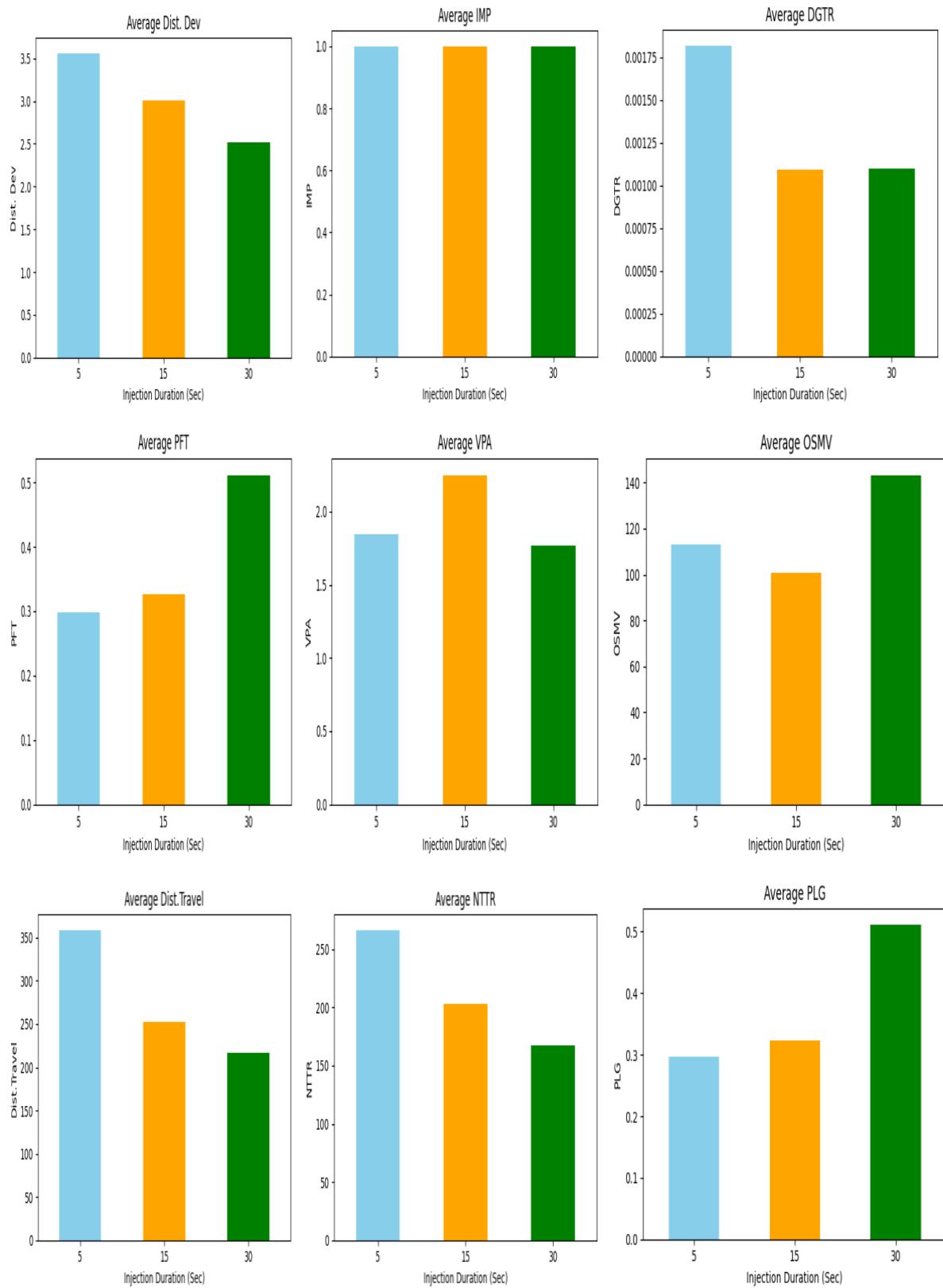


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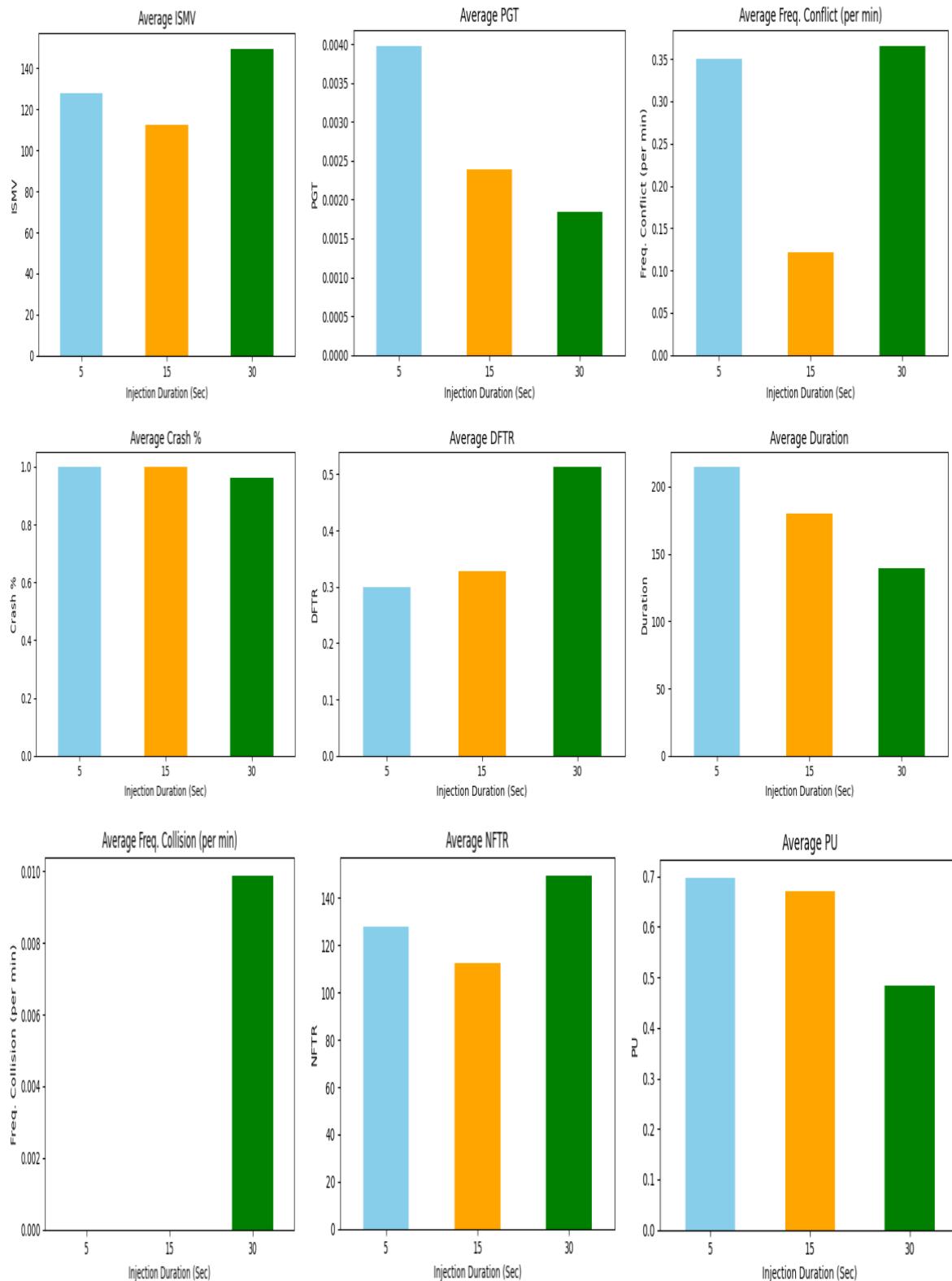


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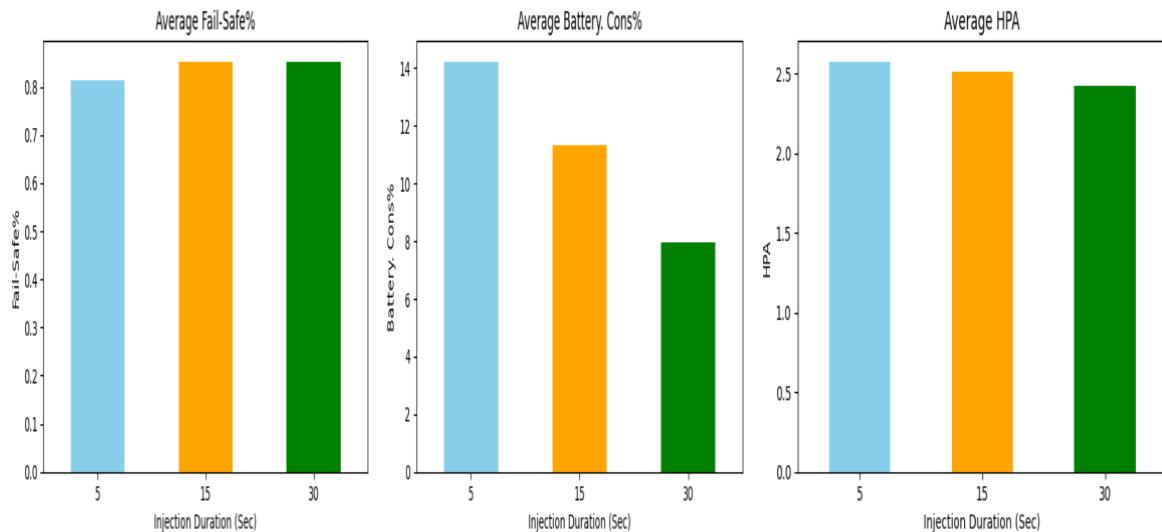
- **Impact of different Injection durations:**



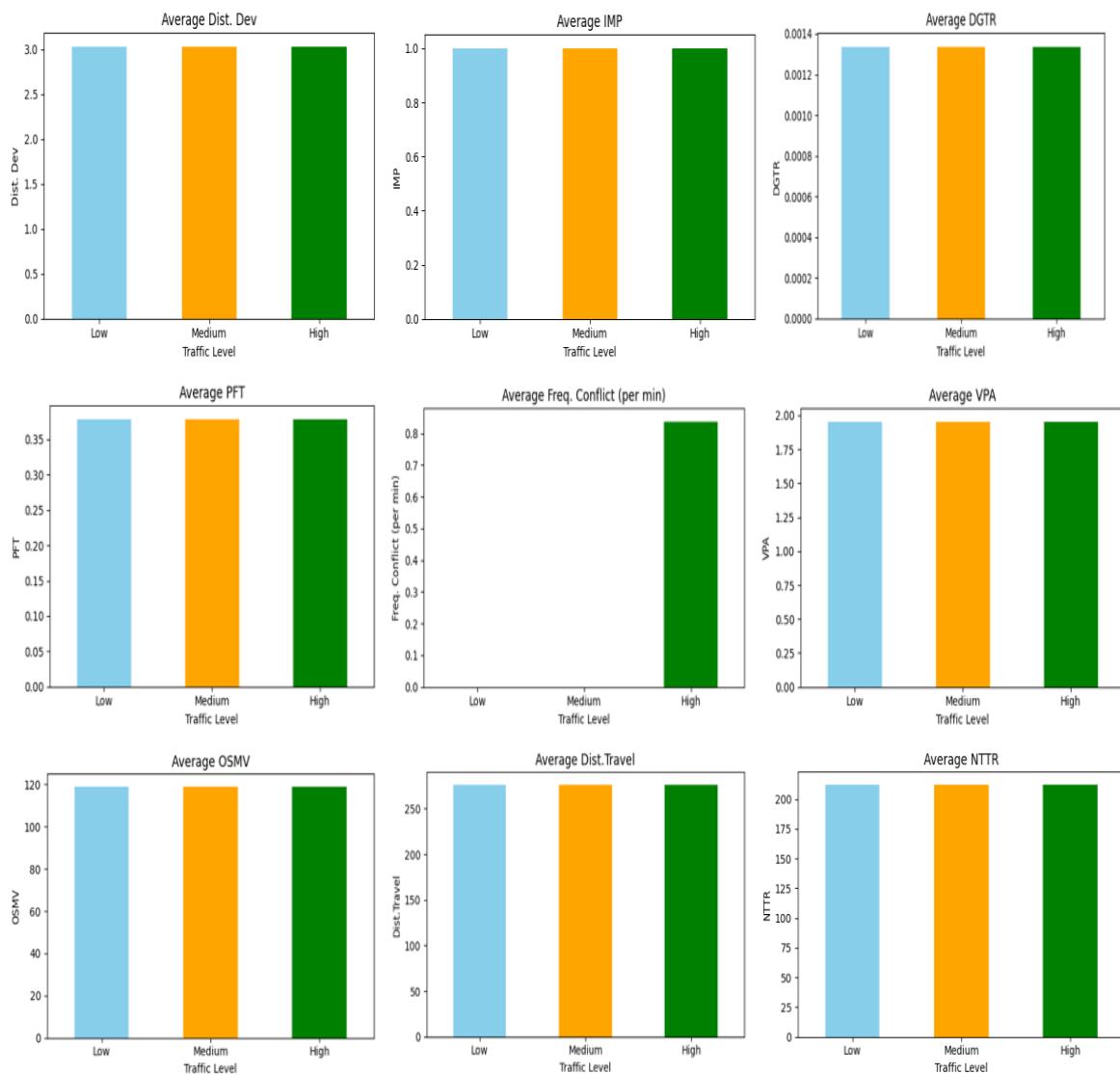
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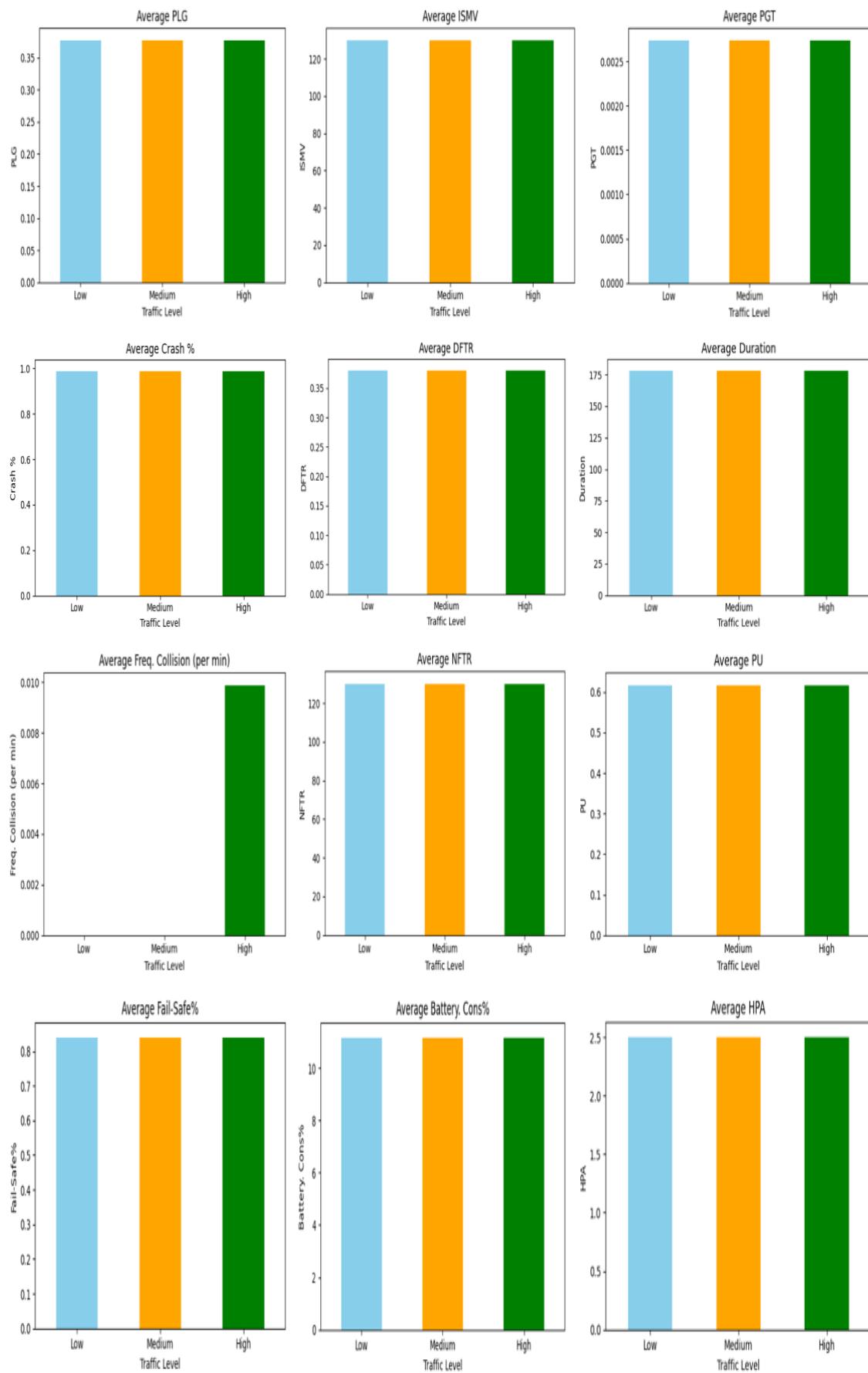
Technical Reports



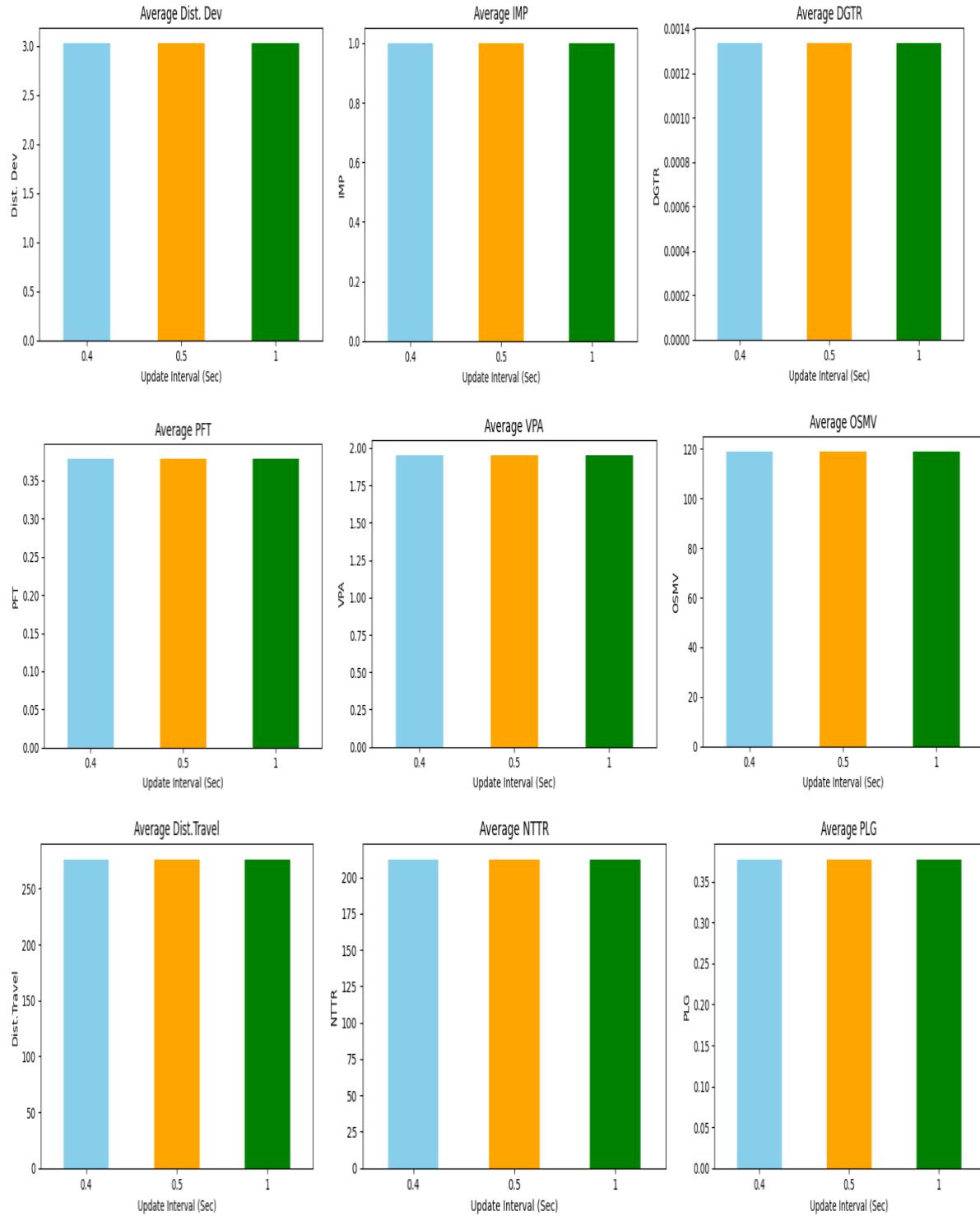
- **Impact of different traffic levels:**



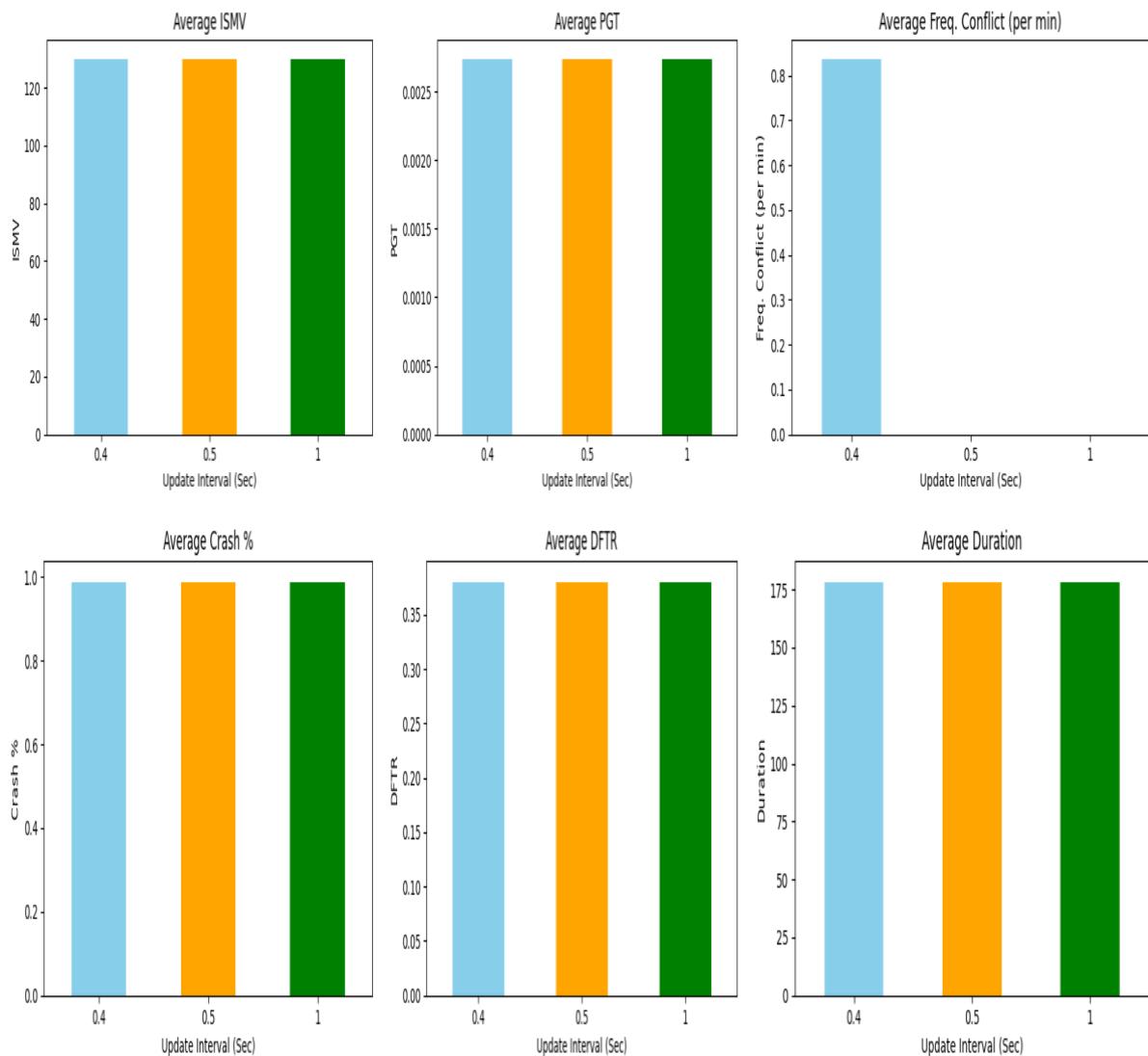
Technical Reports



- **Impact of different update intervals:**



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