7.4 Cooperative Test Cases

The *main goal* of this section is to show the operational capabilities of the *approach* under *UTM supervision*. The minimal UTM functionality set (sec. **??**) has been implemented, including *position notifications mechanism, collision case calculation, resolution enforcement* components.

Test cases cover *well clear breach prevention*, *situation-based avoidance*, and *rules of the air enforcement*.

Coverage of *near miss situations*, *clash incidents* is given implicitly by *safety* and *body* margins (tab. **??**).

1. *Rule-based converging* (sec. 7.4.1) covers *well clear breach* and the *converging rule of the air*, showing determinism and *UTM resolution execution*.
2. *Rule-based head-on* (sec. 7.4.2) covers *well clear breach* and the *head on rule of the air*, showing determinism and *UTM resolution execution*.
3. *Rule-based mixed head on with converging* (sec. 7.4.3) covers *well clear breach* and *head on and converging rules of the air*. The main focus is on a *virtual roundabout* concept when multiple collision cases are clustered into one avoidance maneuver.
4. *Rule-based overtake* (sec. 7.4.4) covers *well clear breach* during *overtaking* by faster UAS.

7.4.1 Rule-Based Converging

Scenario: Two *UAS* are approaching an *airway intersection* at the *same time* in *controlled airspace* (over 500 feet Above the Ground Level). The mutual position of *UAS* can be classified as *Side approach*. Following *collision hazards* are present:

1. *Active Converging Collision Hazard* - An UAS is approaching from the *right side*, which gives him *Right of the Way* and invokes the need to avoid *Intruder* actively.
2. *Passive Converging Collision Hazard* - An UAS is approaching from the *left side*, which gave us *Right of the Way* and imposes an obligation of *active avoidance* on other *UAS*.

Collision Hazards must be addressed by *UTM* service in the following manner:

1. *Each UAS* in particular *Controlled Space* periodically sends synchronized *Position Notification* messages (tab. **??**).
2. *UTM* service receives *Position Notifications* and manages *Collision Case* (tab. **??**) in *Controlled Space*.
3. *UTM* detects *Converging Collision Case* with *Collision Point* in the vicinity.

4. *UTM* service Sends *Mandate* to UAS without *Right of the Way* and implements *Normative Directive* on all *UAS* in the area.

Mission parameters for both UAS systems are defined in (tab. 7.1).

UAS	Position		$\mathcal{WP}_1$
	$[x, y, z]$	$[\theta, \varpi, \psi]$	
1	$[0, 20, 0]^T$	$[0°, 0°, 0°]^T$	$[40, 20, 0]^T$
2	$[20, 0, 0]^T$	$[0°, 0°, 90°]^T$	$[20, 40, 0]^T$

Table 7.1: Mission setup for *Rule based converging* scenario.

Assumptions: Following assumptions are valid for this test:

1. *Controlled Airspace Airworthiness* - UAS system is equipped with necessary controlled airspace equipment like ADS-B In/Out, Radar, Transponder, etc. Moreover, airworthy *UAS* can precisely follow *UTM directives* (max. 5 % deviation).

2. *C2 (Command & control) Link Established* - necessary for (UAS $\leftrightarrow$ UAS) and (UAS $\leftrightarrow$ UTM) communication. If *C2* link is lost the *UAS* will enter into *Emergency avoidance mode.*

3. *Decision frame synchronization with UTM* - necessary in discrete C2 environment otherwise *safety margins* needs to be *bloated.*

4. *Both UAS have identical cruising speed* - simplification impacting *UTM* service implementation. *Obstacle Avoidance Framework* can comprehend various intruders speed, with proper *UAS* directives.

Main Goal: Show possibility of *Converging situation resolution* with *forced safety margin* by *UAS Traffic Management* system. The *Obstacle Avoidance Framework based on Reach Sets* is used as a *Navigation Module.*

Acceptance Criteria: Following criteria must be met:

1. *Well Clear Condition valid for both UAS* - Both *UAS* must have *minimal required distance* from *other UAS* for all *Converging Maneuver* enforcement time.

2. *Fulfillment of UTM Directives* - Both UAS must stay in a *Navigation mode* for all *Converging Maneuver* enforcement time. *UAS without Right Of the Way* must stay away for the necessary time, before returning to *Original Navigation waypoint* $\mathcal{WP}_1$ following.

Testing Setup: The *standard test setup* for each UAS defined in (tab. **??**, **??**, **??**, **??**, **??**) is used with following parameter override:

1. *Navigation grid - type - ACAS-like* with horizontal enabled *maneuvers*

This *configuration* is based on the assumption that every UAS is in *controlled airspace* in *FL450* (flight level 45000 feet Above Sea Level), without permission for a *climb or descent maneuver*. The *rule engine* is initialized in standard *Rules of the air* configuration (fig. **??**).

There is *UTM* service for given *airspace cluster* calculating *collision cases* (tab. **??**) based on incoming *UAS position notifications* (tab. **??**).

Simulation Run: Notable moments from the *simulation run* (fig. 7.1) are the following:

1. *Collision Case creation* (fig. 7.1a) following events happens in this step:

   a. Two *UAS* are approaching *airway intersection*: UAS 1 (blue) from left and UAS 2 (cyan) from the bottom.

   b. They are going to *collide* at point $\mathcal{C} = [20, 20, 0]^T$ of *Flight Level* (elevation is 45, 000 feet Above Mean Sea Level).

   c. UTM service notices future *Collision Situation* and creates *Collision Case*.

   d. *Converging Directive* for 8 m from *Collision point* is issued for UAS 1 (blue) because UAS 2 (cyan) has the *Right Of the Way*.

   e. *Keep Velocity/Heading Directive* is issued for UAS 2 (cyan) to ensure avoidance maneuver success.

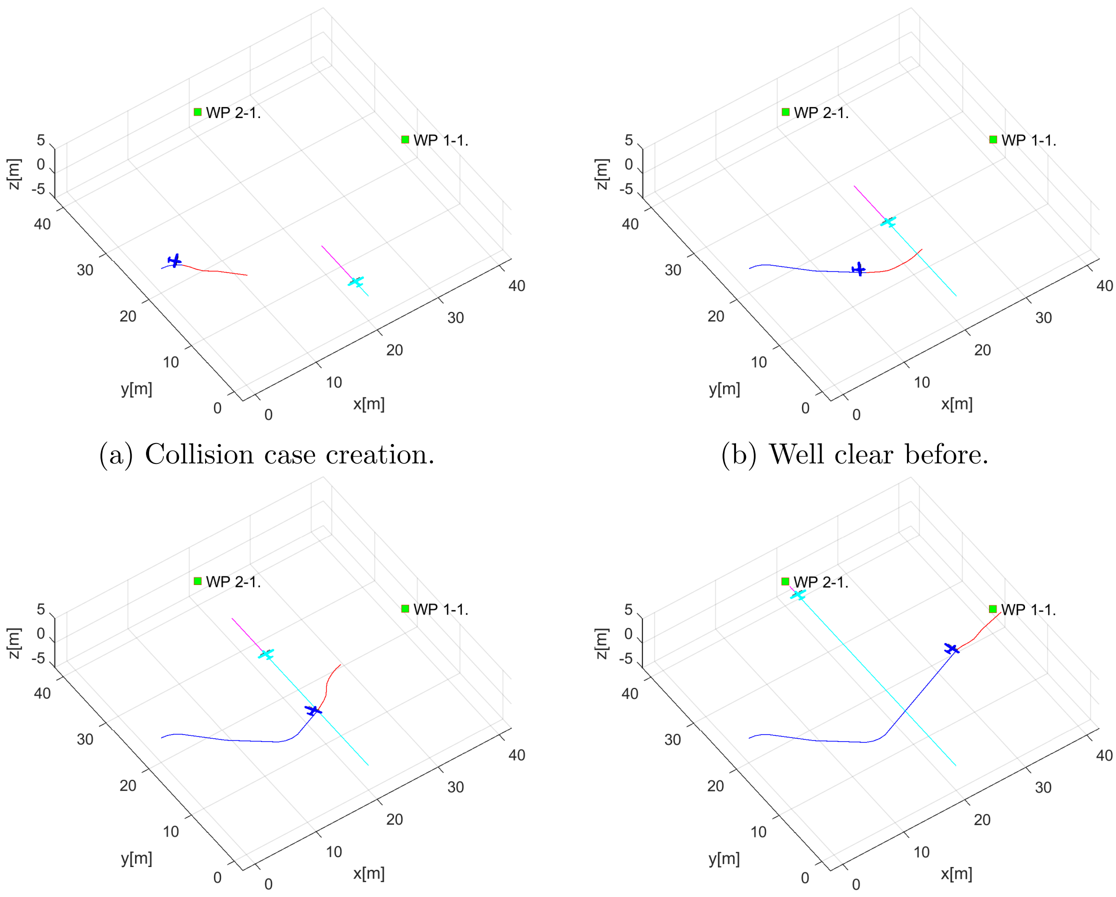
   f. UAS 1 (blue) corrects its heading according to *UTM* directive.

   g. UAS 2 (cyan) stays on claimed course and if its necessary adjust its speed.

2. *Well clear before* (fig. 7.1b) UAS 1 (blue) check the *Collision Point* distance and keeps safe distance given by safety margin. UAS 2 (cyan) checks if there is no intruder in *Avoidance Grid* and if not, stays in *Navigation Mode*.

3. *Well clear after* (fig. 7.1c) UAS 2 (cyan) is *after Collision Point*, it can start negotiations of new speed and heading with UTM. UAS 1 (blue) is still enforced to follow *Converging Maneuver* directive until the outer boundary of *Collision Zone* is reached.

4. *Waypoints reach* (fig. 7.1d) UAS 1 (blue) leaves the outer boundary of the *Collision zone*. Leaving *Converging Maneuver Directive*. UTM closes *Collision Case*.



(a) Collision case creation.

(b) Well clear before.

(c) Well clear after.

(d) Waypoints reach.

Figure 7.1: Test scenario for *Rule-based converging.*

Collision Case Calculation: For test scenario in (fig. 7.1) where UAS 1 (blue) is converging to avoid UAS 2 (cyan) the *Collision Case* (tab. 7.2) have been calculated.

The *Collision point* is at $[20, 20, 0]$ in *Flight Level* $FL450$ coordinate frame.

The *angle of approach* was evaluated as 90° which indicates *converging maneuver* in range $70^\circ \leq angleOfApproach < 130^\circ$.

The *mutual position* of UAS 1 (blue) and UAS 2(cyan) is giving the roles: *Right Of the Way* for UAS 2 (cyan) and *Converging* for UAS 1 (blue).

The *safety margin* for *Well Clear* was determined as $3m$ for UAS 1 and $5m$ for UAS 2. (Note: Well Clear Margin is usually much greater than Near Miss margin). The *Combined Case* margin which was enforced was $8m$. The mutual distance cannot go below this threshold.

Collision Case						Margins	
id	UAS	role	collision point	angle of approach	type	safety	case
1-2	1	Converging	$[20, 20, 0]^T$	90°	Converging	3	8
	2	Right o. W.				5	

Table 7.2: Collision case for *Rule-based converging* scenario.

Distance to Safety Margin Evolution: The safety margin values (well clear) (fig. 7.2) in controlled airspace are much greater than in non-controlled airspace (near miss) (fig. **??**)

The enforced rule was (rule **??**) with parameters: Collision Point $[20, 20, 0]^T$ and *Safety Margin* 8 m as given by Collision Case (tab. 7.2).

The mutual *UAS distance* (blue line) does not go over *Safety Margin* (red line), which means UAS 1 well clear margin of 3 m and UAS 2 well clear margin of 5 m are not broken (fig. 7.2).

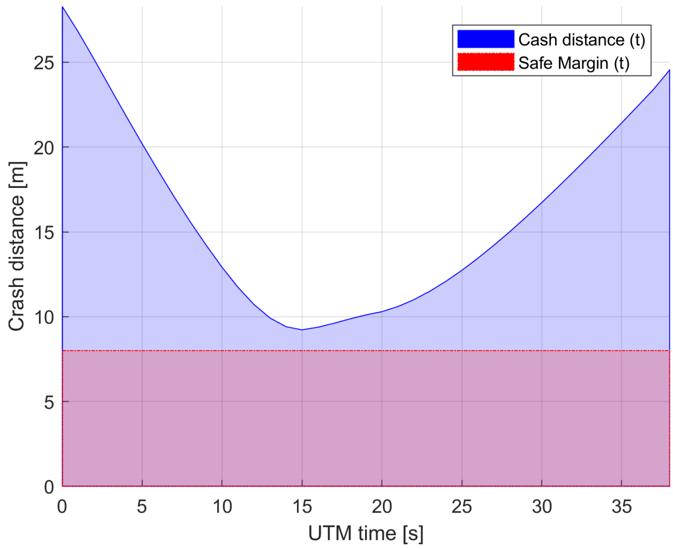


Figure 7.2: Distance to safety margin evolution for the *rule-based converging scenario*.

Distance to Safety Margin Peaks: *Distance to safety margin peaks* (tab. 7.3) represent the proximity on UAS mutual distance to *breach of well clear condition* (safety margin). The *breach of well clear condition* was not achieved. The *minimal distance to the safety margin* was 1.2240 m. The *maximal distance to safety margin* was 20.2843 m which represent distance in a time of *Collision Case Creation*.

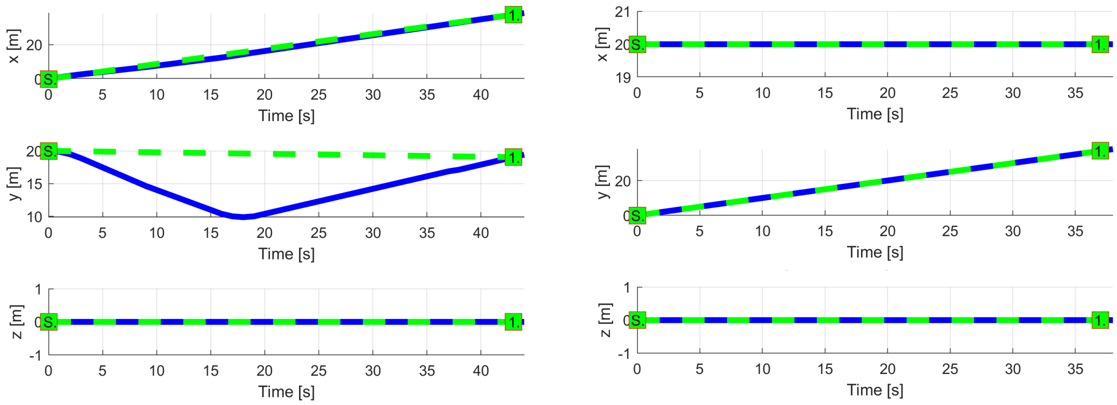
UAS:	Distance to Safety Margin		
	min	max	breach
1-2	1.2240	20.2843	false

Table 7.3: Distance to safety margin peaks for the *rule-based converging scenario*.

Path Tracking Performance: *Path tracking* is displayed in (fig. 7.3). The *UAS* trajectory is divided into *X, Y, Z axis tracking over UTM Time*. The *Reference Trajectory* (green dashed line) interconnect starting position of UAS (green square marked S) a goal waypoint (green square marked 1). The *Executed Trajectory* (solid blue line) reflects real UAS trajectory.

1. UAS 1. (fig, 7.3a) do steady right side *converging maneuver* (y-axis).

2. UAS 2. (fig. 7.3b) follows the reference trajectory precisely because it has the *Right Of Way*.



(a) UAS 1. (b) UAS 2.

Figure 7.3: *Trajectory tracking* for *Rule-based converging* test case.

Path Tracking Deviations: Deviations (tab. 7.4) are in *expected ranges*, considering the *mission plans* (tab. 7.1) and *Collision Case* safety margin of $8m$.

The minimal deviation distance was expected at the value of *safety margin* ($8m$). The maximal deviation was $10.22m$ which is acceptable due the space discretization, UAS dynamic, and, *dynamic decision time*.

Param.	UAS 1 $\mathcal{WP}_1$	UAS 2 $\mathcal{WP}_1$
$\max \lvert x \rvert$	0	0
$\max \lvert y \rvert$	10.22	0
$\max \lvert z \rvert$	0	0
$\max dist.$	10.22	0

Table 7.4: Path tracking properties for *Rule-based converging* scenario.

Computation Load: The *computation load* for *scenario* (fig.7.4) shows used time (y-axis) over decision frame (x-axis).

The *computation time* is slightly increased for avoiding UAS 1 during avoidance. The initial increase of computation time UAS 2 is caused by UTM communication demand.

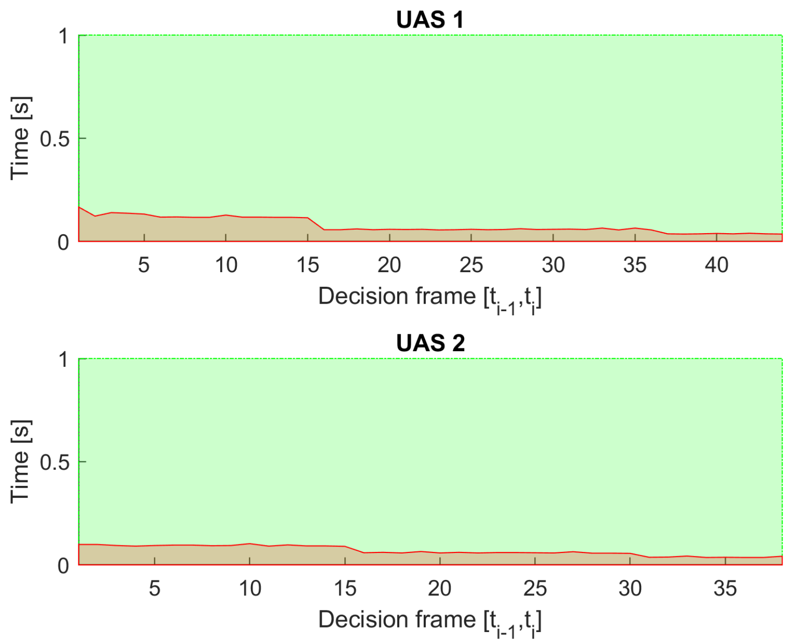


Figure 7.4: Computation time for *Rule-based converging* scenario.

7.4.2 Rule-Based Head-On

Scenario: Two *UAS* are going on the same *airway* in same *flight level* in the opposite direction in *controlled airspace* (over 500 feet Above the Ground Level). The *mutual position* of UAS can be classified as *Side Approach*. Following *collision hazard* is present:

1. *Head-on Collision Hazard* - An *UAS* is approaching from opposite direction which invokes need to avoid *Collision Point* actively.

Head on Collision Hazard must be addressed by *UTM* service in the following manner:

1. *Each UAS* in particular *Controlled Space* periodically sends synchronized *Position Notification* messages (tab. **??**).

2. *UTM* service receives *Position Notifications* and manages *Collision Cases* (tab. **??**) in *Controlled Space*.

3. *UTM* detects single *Head on Collision Cases* with *Collision Point* in the vicinity.

4. *UTM* service creates *Virtual Roundabout* and implements *Normative Directive* on both *UAS*.

Mission parameters for four UAS systems are defined in (tab. 7.5).

UAS	Position		$\mathcal{WP}_1$
	$[x,y,z]$	$[\theta,\varpi,\psi]$	
1	$[0,20,0]^T$	$[0°,0°,0°]^T$	$[45,20,0]^T$
2	$[40,20,0]^T$	$[0°,0°,180°]^T$	$[-5,20,0]^T$

Table 7.5: Mission setup for *Rule-based head-on* scenario.

Assumptions: Following assumptions are valid for this test:

1. *Controlled Airspace Airworthiness* - UAS system is equipped with necessary controlled airspace equipment like ADS-B In/Out, Radar, Transponder, etc. Moreover, airworthy *UAS* can precisely follow *UTM directives* (max. 5 % deviation).

2. *C2 (Command & control) Link Established* - necessary for (UAS ↔ UAS) and (UAS ↔ UTM) communication. If *C2* link is lost the *UAS* will enter into *Emergency avoidance mode.*

3. *Decision frame synchronization with UTM* - necessary in discrete $C2$ environment otherwise *safety margins* needs to be *bloated.*

4. *Both UAS have identical cruising speed* - simplification impacting *UTM* service implementation. *Obstacle Avoidance Framework* can comprehend various intruders speed, with proper *UAS* directives.

Main Goal: Show possibility of *Head-on situation resolution* with *forced safety margin* by *UAS Traffic Management* system. The *Obstacle Avoidance Framework based on Reach Sets* is used as a *Navigation Module.*

Acceptance Criteria: Following criteria must be met:

1. *Well Clear Condition valid for both UAS* - Both *UAS* must have *minimal required distance* from *other UAS* for all *Virtual Roundabout* enforcement time.

2. *Fulfillment of UTM Directives* - Both UAS must stay in a *Navigation mode* for all *Virtual Roundabout* enforcement time. Both *UAS* must stay on *Virtual Roundabout* for the necessary time, before leaving for *Original Navigation waypoint* $\mathcal{WP}_1$.

Testing Setup: The *standard test setup* for each UAS defined in (tab. **??**, **??**, **??**, **??**, **??**) is used with following parameter override:

1. *Navigation grid - type - ACAS-like* with *horizontal enabled maneuvers.*

This *configuration* is based on the assumption that both UAS is in *controlled airspace* in *FL450* (flight level 45000 feet Above Sea Level), without permission for a *climb or descent maneuver.* The *rule engine* is initialized in standard *Rules of the air* configuration (fig. **??**).

There is *UTM* service for given *airspace cluster* calculating *collision cases* (tab. **??**) based on incoming *UAS position notifications* (tab. **??**).

Simulation Run: Notable moments from the *simulation run* (fig. 7.5) are the following:

1. *Collision Case creation* (fig. 7.5a) following events happens in this step:

   a. Two UAS are on the same airway approaching each other from the opposite direction, UAS 1 (blue) from the left, UAS 2 (cyan) from the right.

   b. They are going to *collide* at point $\mathcal{C} = [20, 20, 0]^T$ of *Flight Level* (Elevation is 45, 000 feet Above Mean Sea Level).

   c. UTM service notices future *Collision Situation* and creates *Collision Case.*

   d. *Virtual Roundabout* is created at *collision point* with radius $10m$. UTM issues directive for both UAS to avoid collision point from different sides.

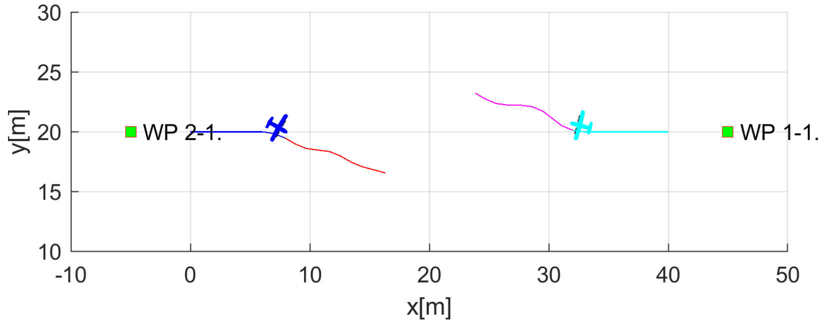
   e. UAS 1 (blue) receives a directive to avoid *Collision Point* from the *right side* (downside in GCS). UAS 2 (cyan) receives a directive to avoid *Collision Point* from the *right side* (upside in GCS).

   f. Both UAS enters into *Virtual Roundabout.*

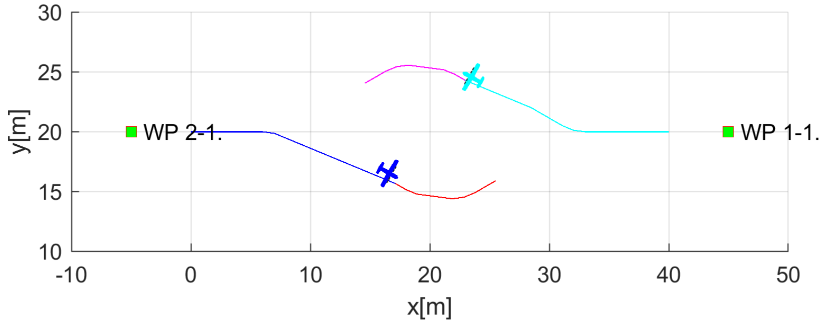
2. *Well clear before* (fig. 7.5b) UAS 1 (blue) is keeping *enforced safety margin* (10 m) from *collision point* and *UAS 2 position.* The *Virtual Roundabout* is enforced until the (*Collision point*) is reached by both UAS. Both UAS stays in *Navigation Mode.*

3. *Well clear after* (fig. 7.5c) UTM notices that *Collision point level* has been reached by both UAS. UTM renounce *Directives* and enables a return to *Original Waypoint* $\mathcal{WP}_1$. Both UAS starts to converging to *Original waypoint* (because possible collision was averted).

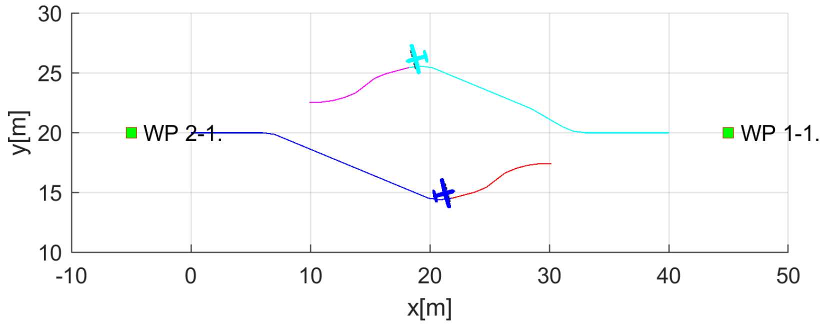
4. *Waypoint reach* (fig. 7.5d) Both UAS reaches respective goal points.



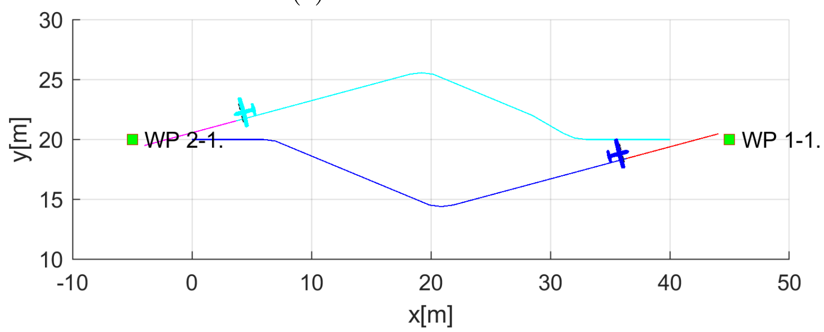
(a) Collision case creation.



(b) Well clear before.



(c) Well clear after.



(d) Waypoints reach.

Figure 7.5: Test scenario for the *rule-based head-on approach* (virtual roundabout).

Collision Case Calculation: For test scenario in (fig. 7.5) where UAS 1 (blue) have head-on collision with UAS 2 (cyan), *Collision Case* have been calculated (tab. 7.6).

The *Collision point* is at $[20, 20, 0]^T$ in Flight Level $FL450$ coordinate frame.

The *angle of approach* was evaluated as 180° which indicates *Head-on Approach* due to the $130° \leq angleofApproach \leq 180°$ conditions.

The *mutual position* of UAS 1 (blue) and UAS 2 (cyan) is giving the roles of *Roundabout* to *both* UAS.

The *safety margin* for *Well Clear* was determined as $5m$ for UAS 1 and UAS 2. The combined *Case Margin* is 10 m, which is sum of both. The *mutual distance* cannot go below this threshold.

Collision Case						Margins	
id	UAS	role	collision point	angle of approach	type	safety	case
1-2	1	Roundabout	$[20, 20, 0]^T$	180°	Head on	5	10
	2	Roundabout				5	

Table 7.6: Collision case for the *rule-based head-on* scenario.

Distance to Safety Margin Evolution: The safety margin values (well clear) (fig. 7.6) in controlled airspace are much larger than in non-controlled airspace (near miss) (fig. **??**).

The enforced rule was (rule **??**) with parameters: Collision Point $[20, 20, 0]^T$ and *Safety Margin* 10 m as given by Collision Case (tab. 7.6).

The mutual *UAS distance* (blue line) does not go over *Safety Margin* (red line) which means both UAS well clear margins are not broken by any means (fig. 7.5).

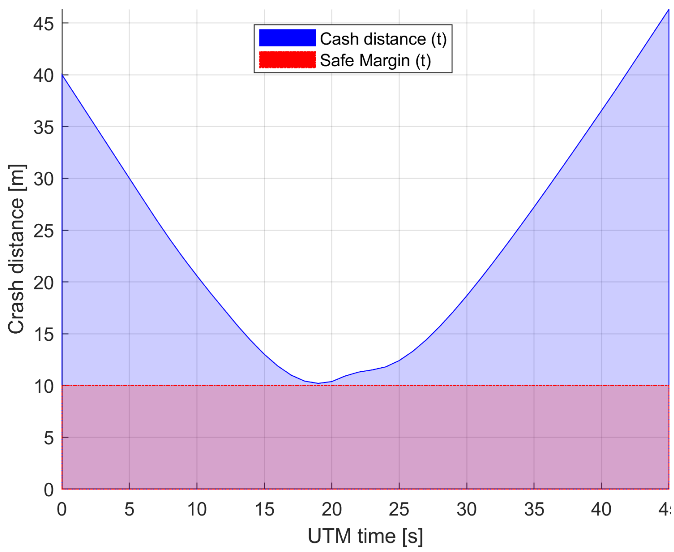


Figure 7.6: Distance to safety margin evolution for the *rule-based head-on scenario.*

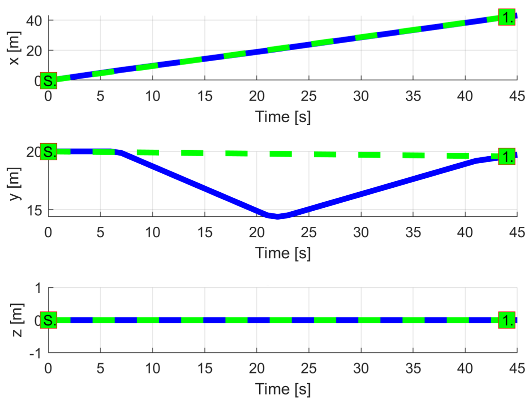
Distance to Safety Margin Peaks: Given by (tab. 7.7) represents the proximity on UAS mutual distance to *well clear condition* breach. The breach of *well clear condition* was not achieved. The *minimal distance to the safety margin* was 0.2084 m. The *maximal distance to safety margin* was $36.3253m$ which represents distance at *Collision Case* closing.

UAS:	Distance to Safety Margin		
	min	max	breach
1-2	0.2084	36.3253	false

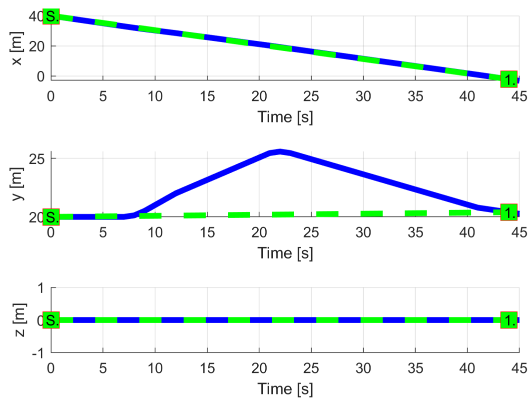
Table 7.7: *Rule-based head-on* safety margin distances.

Path Tracking Performance: *Path tracking* is displayed in (fig. 7.7). The *UAS* trajectory is divided into *X, Y, Z axis tracking over UTM Time*. The *Reference Trajectory* (green dashed line) interconnect starting position of UAS (green square marked S) a goal waypoint (green square marked 1). The *Executed Trajectory* (solid blue line) reflects real UAS trajectory.

1. UAS 1. (fig, 7.7a) do steady right side *roundabout maneuver* (y-axis).
2. UAS 2. (fig. 7.7b) do steady right side *roundabout maneuver* (y-axis).



(a) UAS 1.



(b) UAS 2.

Figure 7.7: *Trajectory tracking* for *rule-based head-on* test case.

Path Tracking Deviations: Deviations (tab. 7.8) are in *expected ranges*, considering the *mission plans* (tab. 7.5) and *Collision Case* safety margin of 10m.

Param.	UAS 1	UAS 2
	$\mathcal{WP}_1$	$\mathcal{WP}_1$
$\max\|x\|$	0	0
$\max\|y\|$	5.40	5.40
$\max\|z\|$	0	0
$\max dist.$	5.40	5.40

Table 7.8: Path tracking properties for *rule-based head-on* scenario.

Computation Load: The *computation load* for *scenario* (fig.7.8) shows used time (y-axis) over decision frame (x-axis).

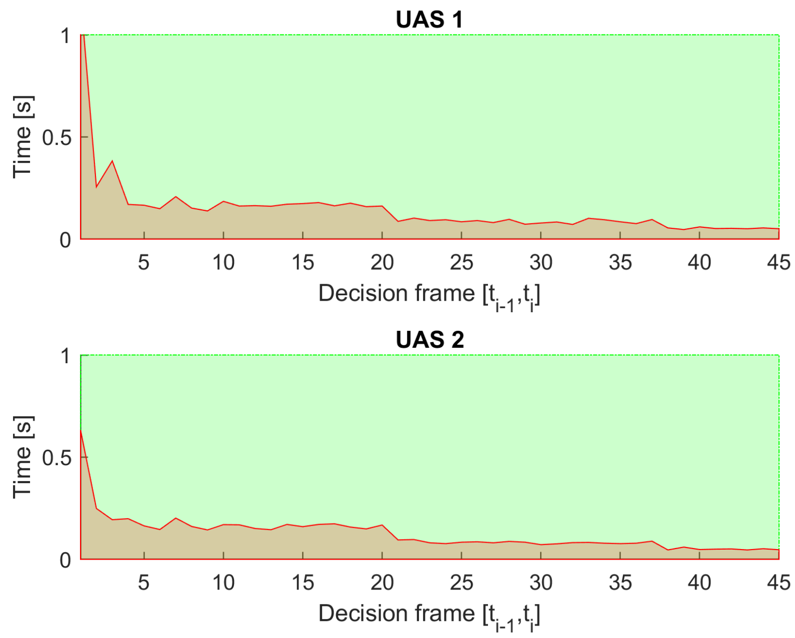


Figure 7.8: Computation time for *rule-based head-on* scenario.

7.4.3 Rule-Based Mixed Head-On with Converging

Scenario: Four *UAS* are approaching an airway *intersection* at the *same time* from *opposite direction* in *controlled airspace* (over 500 feet Above Ground Level). Each *UAS* have following *Collision Hazards*:

1. *Head on Collision Hazard* - An UAS is approaching from opposite direction which invokes need to avoid *Collision Point* actively

2. *Active Converging Collision Hazard* - An UAS is approaching from the *right side*, which gives him *Right of the Way* and invokes the need to avoid *Intruder* actively.

3. *Passive Converging Collision Hazard* - An UAS is approaching from the *left side*, which gave us *Right of the Way* and imposes an obligation of *active avoidance* on other *UAS*.

Note. Presented scenario is *the worst possible situation* in current *manned aviation ATM*.

Mentioned Collision Hazards must be addressed by *UTM* service in the following manner:

1. *Each UAS* in particular *Controlled Space* periodically sends synchronized *Position Notification* messages (tab. **??**).

2. *UTM* service receives *Position Notifications* and manages *Collision Cases* (tab. **??**) in *Controlled Space*.

3. *UTM* detects multiple *Collision Cases* with *Collision Points* in the vicinity.

4. *UTM* service creates *Virtual Roundabout* and implements *Normative Directive* on all *UAS* in the area.

Mission parameters for four UAS systems are defined in (tab. 7.9).

UAS	Position		$\mathcal{WP}_1$
	$[x, y, z]$	$[\theta, \varpi, \psi]$	
1	$[0, 20, 0]^T$	$[0°, 0°, 0°]^T$	$[45, 20, 0]^T$
2	$[40, 20, 0]^T$	$[0°, 0°, 180°]^T$	$[-5, 20, 0]^T$
3	$[20, 0, 0]^T$	$[0°, 0°, 90°]^T$	$[20, 45, 0]^T$
4	$[20, 40, 0]^T$	$[0°, 0°, -90°]^T$	$[45, 20, 0]^T$

Table 7.9: Mission setup for *rule-based mixed* scenario.

Assumptions: Following assumptions are valid for this test:

1. *Controlled Airspace Airworthiness* - UAS system is equipped with necessary controlled airspace equipment like ADS-B In/Out, Radar, Transponder, etc. Moreover, airworthy *UAS* has capability to precisely follow *UTM directives* (max. 5 % deviation).

2. *C2 (Command & control) Link Established* - necessary for (UAS $\leftrightarrow$ UAS) and (UAS $\leftrightarrow$ UTM) communication. If *C2* link is lost the *UAS* will enter into *Emergency avoidance mode.*

3. *Decision frame synchronization with UTM* - necessary in discrete C2 environment otherwise *safety margins* needs to be *bloated.*

4. *Every UAS have identical cruising speed* - simplification impacting *UTM* service implementation. *Obstacle Avoidance Framework* can comprehend various intruders speed, with proper *UAS* directives.

Main Goal: Show possibility of *Virtual Roundabout* invoked by *UTM* directives where *Obstacle Avoidance Framework based on Reach Sets* is used as a *Navigation Module.*

Acceptance Criteria: Following criteria must be met:

1. *Well Clear Condition valid for every UAS* - Each *UAS* must have *minimal required distance* from *other UAS* for all *Virtual Roundabout* enforcement time.

2. *Fulfillment of UTM Directives* - Each UAS must stay in a *Navigation mode* for all *Virtual Roundabout* enforcement time. Each *UAS* must stay on *Virtual Roundabout* for the necessary time, before leaving for *Original Navigation waypoint* $\mathcal{WP}_1$.

Testing Setup: The *standard test setup* for each UAS defined in (tab. **??**, **??**, **??**, **??**, **??**) is used with following parameter override:

1. *Navigation grid - type - ACAS-like* with *horizontal enabled maneuvers*

This *configuration* is based on the assumption that every UAS is in *controlled airspace* in *FL450* (flight level 45000 feet Above Sea Level), without permission for a *climb or descent maneuver*. The *rule engine* is initialized in standard *Rules of the air* configuration (fig. **??**).

There is *UTM* service for given *airspace cluster* calculating *collision cases* (tab. **??**) based on incoming *UAS position notifications* (tab. **??**).

Simulation Run: Notable moments from the *simulation run* (fig. 7.9) are the following:

1. *Collision cases created* (fig. 7.9a) following events happen in this step:

   a. Four *UAS* are approaching airways intersection: *UAS 1* (blue) from left, *UAS 2* (cyan) from right, *UAS 3* (green) from the bottom, *UAS 4* (black) from the top.

   b. They are going to collide at point $[20, 20, 0]^T$ of *Flight level* (elevation is 45, 000 feet Above Mean Sea Level).

   c. *UTM service* notices future *Collision Situations* and creates *Collision Cases.*

   d. There are many *Collision Cases* in the near vicinity. The *Virtual Roundabout* is created with *Safety margin* 15 m.

   e. The *UTM* service then sends a new *Roundabout Directives* to involved *UAS* systems.

   f. Each *UAS* starts *Roundabout Entry Maneuver* by correcting own *Heading* and *Speed* (if its necessary).

2. *Roundabout entry* (fig. 7.9b) - Each *UAS* enters into *Virtual Roundabout* while sending *Roundabout Entrance Notification* to *UTM service.*

3. *Roundabout leave* (fig. 7.9c) following events happens in this step:

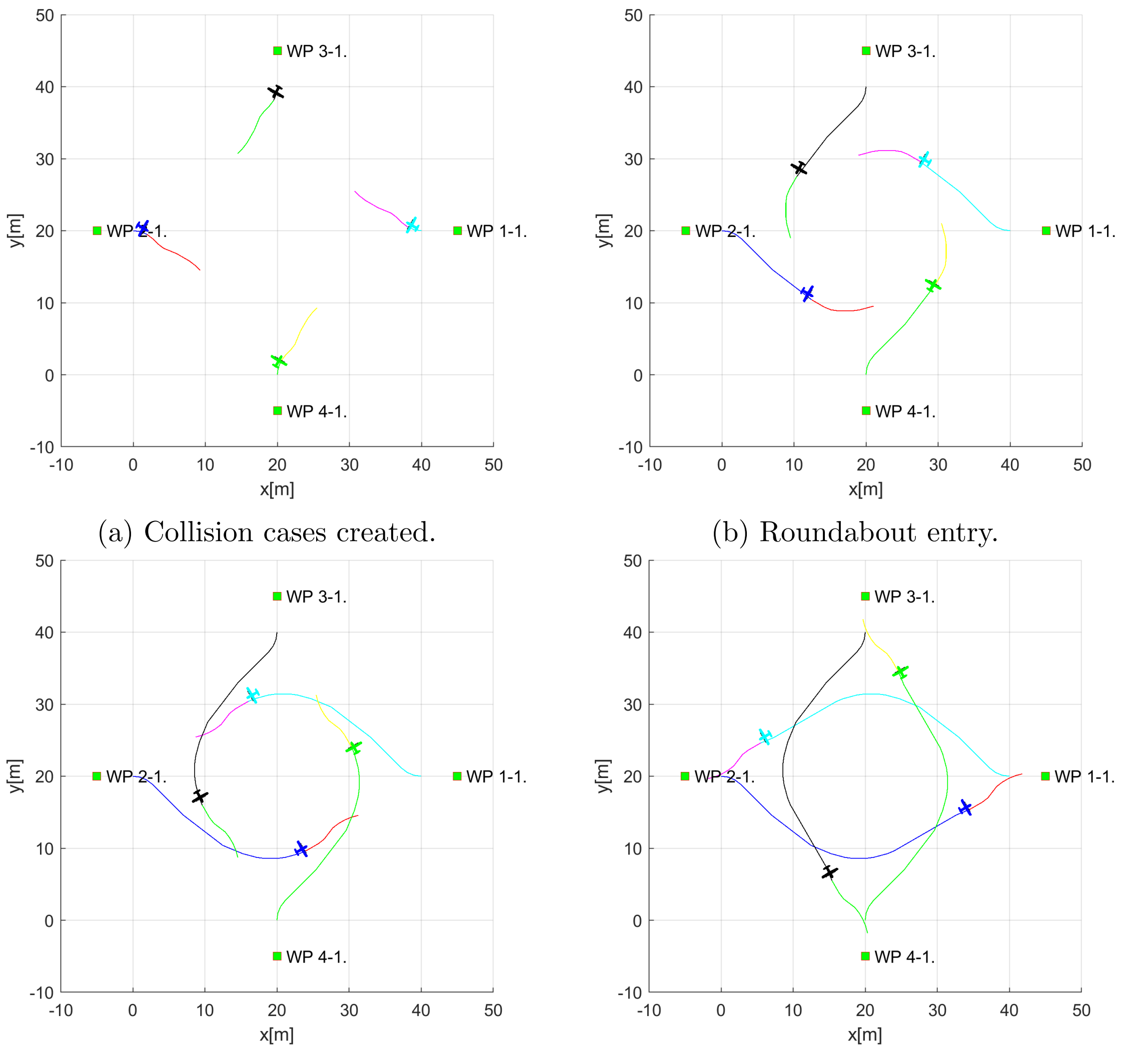
   a. Each *UAS* when is going to approach the level of *Original Goal Waypoint* sends *Roundabout Leave Request.*

   b. UTM system will check if there is *Sufficient Free Space* to leave *Virtual Roundabout.*

   c. The *UTM Service then issues Virtual Roundabout Leave Approval.*

   d. Each *UAS* will correct own heading and speed in the range of received permit.

4. *Situation resolution* (fig. 7.9d) - Each *UAS* is heading away from *Roundabout Center*, there is no active user of *Virtual Roundabout*. *UTM* will remove *Virtual Roundabout* and closes underlying *Collision Cases*. Each *UAS* will reach respective *Original Goal Waypoint*.



(a) Collision cases created. (b) Roundabout entry.

(c) Roundabout leave. (d) Situation resolution.

Figure 7.9: Test scenario for *rule-based mixed* situation with the *self-separation mode*.

Collision Cases Calculation: The set of original *Collision cases* is given in (tab. 7.10).

Each *UAS* has one *Head on*, *Converging passive*, *Converging active* collision hazard. For example *UAS 1* have a *head-on* with *UAS 2*, *converging passive* with *UAS 4*, *converging active* with *UAS 3*. For *UAS 2-4* check *role* in respective *Collision Cases*.

Note. Collision cases calculated by *UTM* are symmetric, which means that collision case for *UAS X, UAS Y* is identical to collision case calculated for *UAS Y, UAS X*, $X \neq Y$.

Safety margin representing *Well Clear Margin* for single *UAS* in *Collision Case* ranges $5{-}8\ m$. *Case margin* representing the minimal mutual distance between two *UAS systems* to remain well clear ranges $12 - 15\ m$.

Merged Collision Case is oversimplified for demonstration purposes. *Merge Case Procedure* is out of the scope of this work due to its extent. Every *Collision Case* shares same *Collision Point* $[20, 20, 0]^T$ in flight level coordinate frame. *Merged Collision Case* type was set as *Roundabout*, due the number of collision case *attendants* is greater than 2. Each *UAS role* has been set as *Roundabout.* The enforced *safety margin* is equal to 15 m, which is the maximum of all *single collision case combined margins.*

Collision Case						Margins	
id	UAS	role	collision point	angle of approach	type	safety	case
1-2	1	Roundabout	$[20, 20, 0]^T$	180°	Head on	8	15
	2	Roundabout				7	
1-3	1	Converging	$[20, 20, 0]^T$	90°	Converging	8	15
	3	Right o.W.				5	
1-4	1	Right o.W.	$[20, 20, 0]^T$	90°	Converging	8	15
	4	Converging				5	
2-3	2	Right o.W.	$[20, 20, 0]^T$	90°	Converging	7	12
	3	Converging				5	
2-4	2	Converging	$[20, 20, 0]^T$	90°	Converging	7	12
	4	Right o.W.				5	
3-4	3	Roundabout	$[20, 20, 0]^T$	180°	Head on	7	14
	4	Roundabout				7	

Merged cases					Safety Margin
id	UAS	role	collision point	type	
1-2-3-4	1	Roundabout	$[20, 20, 0]^T$	Roundabout	15
	2	Roundabout			
	3	Roundabout			
	4	Roundabout			

Table 7.10: Collision cases for *rule-based mixed* scenario.

Distance to Safety Margin Evolution: *Merged Collision Case Safety Margin* is 15 m, and it is valid for all *UAS mutual distances.* The simple condition for *Remain Well Clear* is:

$$crashDistance(UAS_X, UAS_Y, t) \geq 15m, X \neq Y \in \{1, 2, 3, 4\}, t \in utmTime$$

Safety Margin Performance is given in (fig. 7.10). The mutual distance (Crash Distance [m]) between two UAS is denoted as the *blue line.* The enforced safety margin for *Remain Well Clear* condition is denoted as the red line.

Note. Evolution of mutual crash distance is symmetric. In any case, the mutual distance goes under *safety margin*. *Acceptance criterion* for *Well Clear condition* is fulfilled.

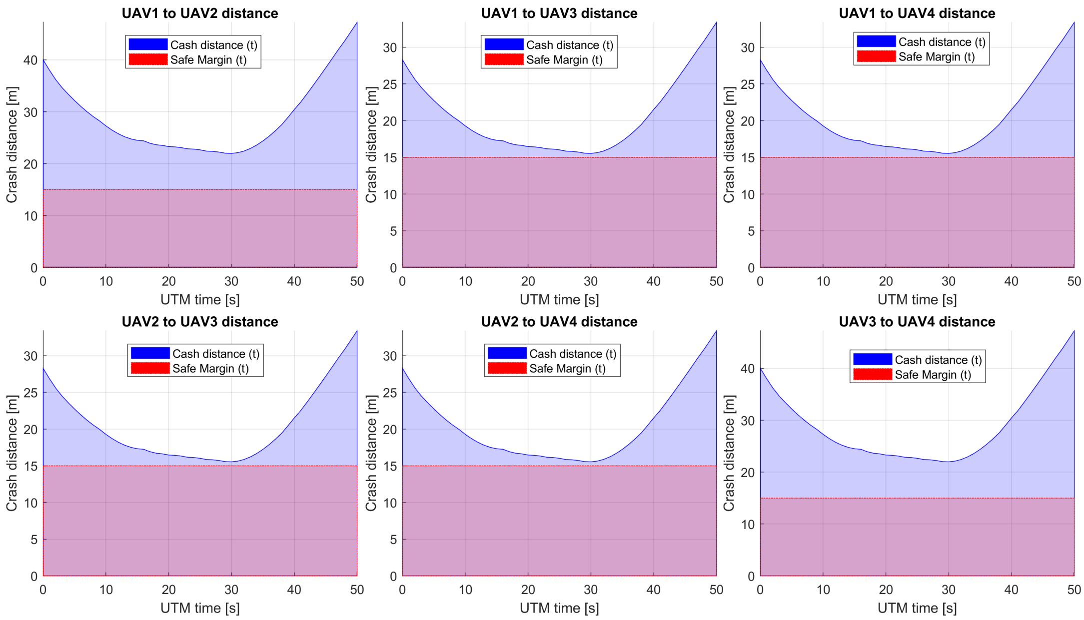


Figure 7.10: Distance to safety margin evolution for *rule-based mixed scenario*.

Distance to Safety Margin Peaks: *Distance to Safety Margin Peaks* (tab. 7.11) represents the proximity of *UAS mutual distance to breach well clear condition*. The *breach condition* was not fulfilled in any combination.

The *minimal distance to safety margin* was 0.5438 *m* between all four *UAS* systems. The *maximal distance to safety margin* ranges between *18 - 32 m* which show advantages of the *virtual roundabout*.

UAS:	Distance to Safety Margin		
	min	max	breach
1-2	6.9823	32.2369	false
1-3	0.5438	18.4015	false
1-4	0.5438	18.4015	false
2-3	0.5438	18.4015	false
2-4	0.5438	18.4015	false
3-4	6.9823	32.2369	false

Table 7.11: Distance to safety margin peaks for *rule-based mixed scenario*.

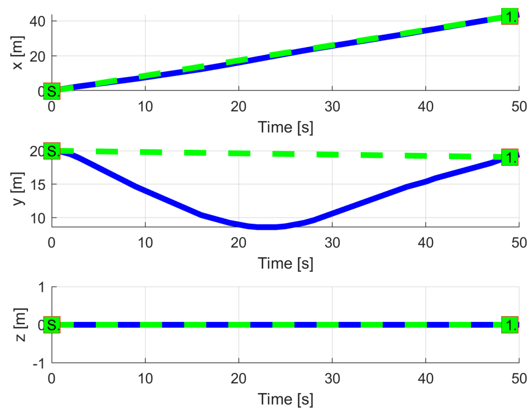
Path Tracking Performance: Path tracking is displayed in (fig. 7.11). The UAS trajectory is divided into *X, Y, Z axis tracking over UTM Time*. The *Reference Trajectory* (green dashed line) is represented as the interconnection between *Start Waypoint* (green square marked S) and *Goal Waypoint* $\mathcal{WP}_1$ (green square marked 1). The *Executed trajectory* (solid blue line) reflects real *UAS* movement.

1. *UAS 1* (fig. 7.11a) is using the bottom portion of *Virtual Roundabout* (-Y values), sticking to the boundary of the *Virtual Roundabout*.

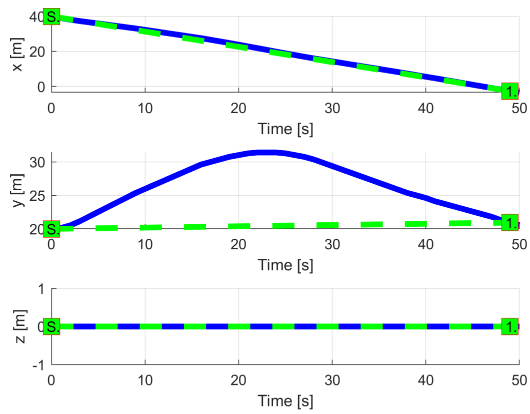
2. *UAS 2* (fig. 7.11b) is using the upper portion of the *Virtual Roundabout*. (+Y values), sticking to the boundary of the *Virtual Roundabout*.

3. *UAS 3* (fig. 7.11c) is using the right portion of the *Virtual Roundabout*. (+X values), sticking to the boundary of the *Virtual Roundabout*.

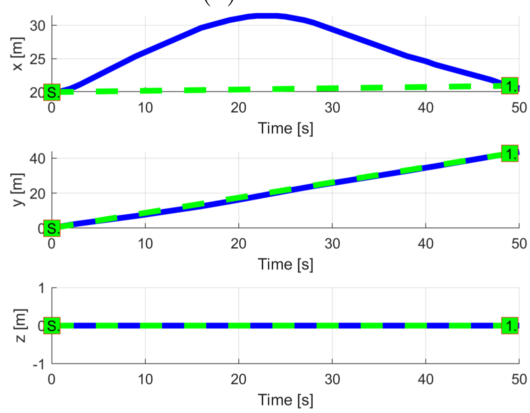
4. *UAS 4* (fig. 7.11d) is using the left portion of the *Virtual Roundabout*. (-X values), sticking to the boundary of the *Virtual Roundabout*.



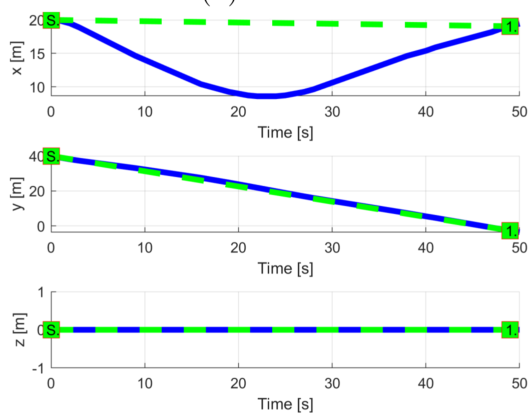
(a) UAS 1.



(b) UAS 2.



(c) UAS 3.



(d) UAS 4.

Figure 7.11: Trajectory tracking for *rule-based mixed* situation test case.

Path Tracking Deviations: *Deviations* (tab. 7.12) are in expected ranges, considering the mission plans (tab. 7.9) and *Merged Case Safety Margin* (15 m).

Param.	UAS 1	UAS 2	UAS 3	UAS 4
	$\mathcal{WP}_1$	$\mathcal{WP}_1$	$\mathcal{WP}_1$	$\mathcal{WP}_1$
$\max\lvert x\rvert$	0	0	11.40	11.40
$\max\lvert y\rvert$	11.40	11.40	0	0
$\max\lvert z\rvert$	0	0	0	0
$\max dist.$	11.40	11.40	11.40	11.40

Table 7.12: Path tracking properties for *rule-based mixed* scenario.

Computation Load: The *computation load* for *scenario* (fig.7.12) shows used time (y-axis) over decision frame (x-axis).

The *computation time* for each UAS has the same evolution. The *load* is higher during avoidance maneuver on the *virtual roundabout*.

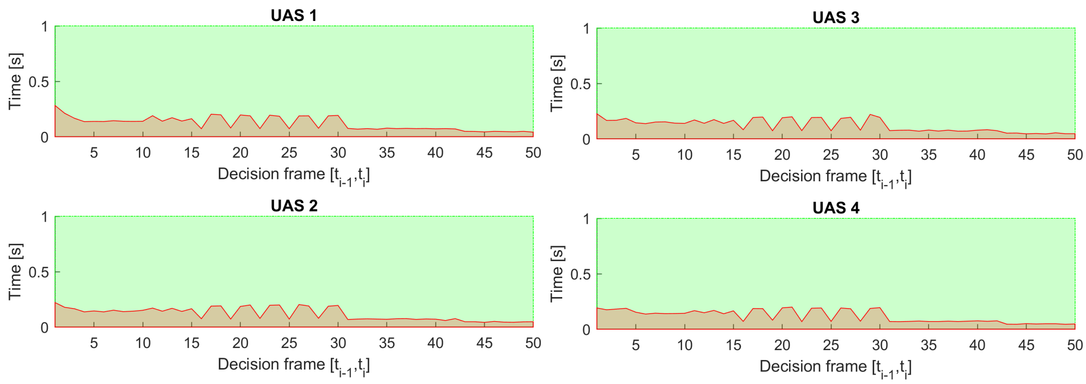


Figure 7.12: Computation time for *rule-based multiple* scenario.

7.4.4 Rule-Based Overtake

Scenario: Two UAS are flying in the *controlled airspace* (over 500 feet Above Ground Level) on the *airway* (in the same direction). *Slower UAS* is in front of *Faster UAS*. There is possibility of a *collision* or a *near miss incident* or a *well clear breach*. The *Faster UAS* (Overtaking) must contact *UTM* service and ask for *overtake permission*. Scenario steps:

1. *Faster UAS* (Overtaking) notices *UTM* service about *Slower UAS* (Overtaken). (This step is Optional.)

2. *UTM* service issues *Directives* to all *UAS* in the area.

3. *Overtake Directive* is received by *Faster UAS* (Overtaking) and *Slower UAS* (Overtaken).

4. *Faster UAS* (Overtaking) mission plan is altered to reflect *Overtake directive*, *Divergence Waypoint* and *Convergence Waypoint* are added.

5. *Faster UAS* (Overtaking) safely overtakes *Slower UAS* (Overtaken) without breaking *Well clear* condition.

Mission parameters for both *UAS* systems are defined in (tab. 7.13).

UAS	Position		$\mathcal{WP}_1$
	$[x, y, z]$	$[\theta, \varpi, \psi]$	
1	$[-40, 20, 0]^T$	$[0°, 0°, 0°]^T$	$[110, 20, 0]^T$
2	$[-20, 20, 0]^T$	$[0°, 0°, 0°]^T$	$[80, 20, 0]^T$

Table 7.13: Mission setup for all *Rule based overtake* scenarios.

Assumptions: Following assumptions are valid for this test:

1. *Controlled Airspace Airworthiness* - UAS system is equipped with necessary controlled airspace equipment like ADS-B In/Out, Radar, Transponder, etc. Moreover, airworthy *UAS* has capability to precisely follow *UTM directives* (max. 5 % deviation).

2. *C2 (Command & control) Link Established* - necessary for (UAS ↔ UAS) and (UAS ↔ UTM) communication. If *C2* link is lost the *UAS* will enter into *Emergency avoidance mode.*

3. *Decision frame synchronization with UTM* - necessary in discrete C2 environment otherwise *safety margins* needs to be *bloated.*

Main Goal: Show possibility of *Overtake Maneuver* invoked by the *UTM Directive* (event-based flight constraint).

Acceptance Criteria: Following criteria must be met:

1. *Proper passing of Divergence/Convergence Waypoint* - a minimal distance of *UAS trajectory* to *Divergence/Convergence waypoint* must be below the passing threshold. Waypoints need to be passed in given order (Divergence 1^{st}, Convergence 2^{nd}).

2. *Slower UAS (Overtaken) keeps Right of the Way* - the UAS with lesser maneuverability does not stand a chance in avoidance situation, it needs to keep its *Right of the Way.*

3. *Both UAS does not breach Well Clear (safety) Margin* - mutual distance does not get through *calculated Safety Margin.*

Testing Setup: The *standard test setup* for each UAS defined in (tab. **??**, **??**, **??**, **??**, **??**) is used with following parameter override:

1. *Navigation grid - type - ACAS-like* with *horizontal enabled maneuvers.*

This *configuration* is based on the assumption that every UAS is in *controlled airspace* in *FL450* (flight level 45000 feet Above Sea Level), without permission for a *climb or descent maneuver*. The *rule engine* is initialized in standard *Rules of the air* configuration (fig. **??**).

There is *UTM* service for given *airspace cluster* calculating *collision cases* (tab. **??**) based on incoming *UAS position notifications* (tab. **??**).

Simulation Run: Notable moments from the *simulation run* (fig. 7.13) are the following:

1. *Collision case creation* (fig.7.13a) - *Faster UAS* (blue) receives *UTM Directive* to invoke *Overtake Rule* (tab. **??**). *Slower UAS* (magenta) receives *UTM Directive* to keep *Right of the Way* and warning that is going to be *Overtaken*. *Faster UAS* (blue) creates two *virtual waypoints*:

   a. *Divergence waypoint* at position $[0, 14, 0]^T$.

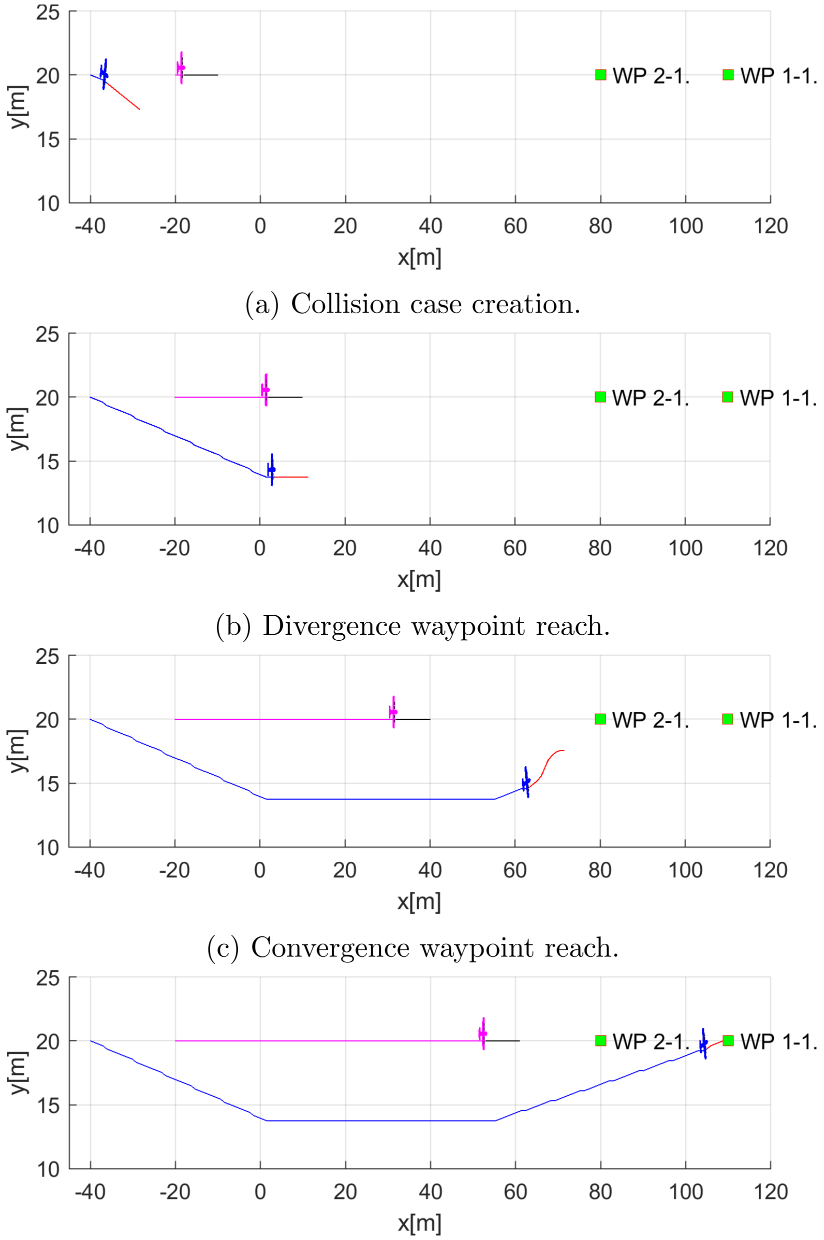
   b. *Convergence waypoint* at position $[24, 14, 0]^T$.

   Faster UAS then sets *Divergence waypoint* as *Goal waypoint*, and It starts to overtake maneuver while checking mutual distance.

2. *Divergence waypoint reach* (fig. 7.13b) - *Faster UAS* (blue) successfully reached *Divergence Waypoint*, setting *Convergence Waypoint* as new *Goal waypoint.*

3. *Convergence waypoint reach* (fig. 7.13c) - *Faster UAS* (blue) successfully reached *Convergence Waypoint*, setting *Original Goal Waypoint* as new *Goal waypoint.* The *UTM* service is notified from *Faster UAS* (blue) that *Overtaken Maneuver* has been completed. UTM *acknowledges* maneuver competition and It sends a notification to *Slower UAS* (magenta) that *Overtake Maneuver* is finished. *Slower UAS* (magenta) was successfully overtaken.

4. *Original waypoint reach* (fig. 7.13d) - *Faster UAS* (blue) successfully reached *Original Waypoint*, Starting landing Sequence.



(a) Collision case creation.

(b) Divergence waypoint reach.

(c) Convergence waypoint reach.

(d) Original waypoint reach.

Figure 7.13: Test scenario for *rule-based Overtake* (double speed of overtaking aircraft).

Collision Case Calculation: The *Collision Case* (tab. 7.14) was calculated according to the *Collision Calculation process* (sec. **??**). *Faster UAS* (1) has *Overtaking* role, and *Slower UAS* has the *Right of Way*. *Collision Point* is direct type at $[0.20.0]^T$. *Collision case type* was set based on *angle of approach* $0°$ as *Overtake*. The *Safety Margin* was set as *5 m*.

Collision Case						Margins	
id	UAS	role	collision point	angle of approach	type	safety	case
1-2	1	Overtaking	$[0, 20, 0]^T$	0°	Overtake	5	5
	2	Right o.W.				5	

Table 7.14: Collision case for *Rule-based Overtake* scenario 2x speed.

Overtake Speed: Divergence/Convergence Waypoints *Divergence waypoints* have been calculated according to (eq. **??**), and, *Convergence Waypoints* have been calculated according to (eq. **??**). Following *Speed Differences* were taken into account (Faster/Slower UAS speed ratio): *2x, 3x, 4x.* Following observations can be made:

1. *The distance between Divergence and Convergence waypoint* is decreasing with increasing *speed difference.*

2. *Divergence waypoint* is moving *back/right* in *UAS Local Coordinate Frame* with Increasing *speed difference.*

3. *Convergence waypoint* is moving like *Divergence waypoint* but a little bit faster.

Speed diff.	Divergence waypoint	Divergence difference	Convergence waypoint	Convergence difference	Final waypoint
2x	$[0, 14, 0]^T$		$[24, 14, 0]^T$		$[110, 20, 0]^T$
		$[-10, -1, 0]^T$		$[-8, -1, 0]^T$	
3x	$[-10, 13, 0]^T$		$[16, 13, 0]^T$		$[110, 20, 0]^T$
		$[-3.4, -1, 0]^T$		$[-1.3, -1, 0]^T$	
4x	$[-13.4, 12, 0]^T$		$[14.7, 12, 0]^T$		$[110, 20, 0]^T$

Table 7.15: Convergence and divergence waypoints for various speed differences.

Overtake Speed: Impact on Trajectory Overtake *speed difference* is visible in (fig. 7.14). The *Slower vehicle trajectory*(cyan) is following *standard mission waypoints.* The *Faster vehicle trajectory* for 2x (blue), 3x (green), 4x (black) are following *Divergence/Convergence* waypoints from (tab. 7.15).

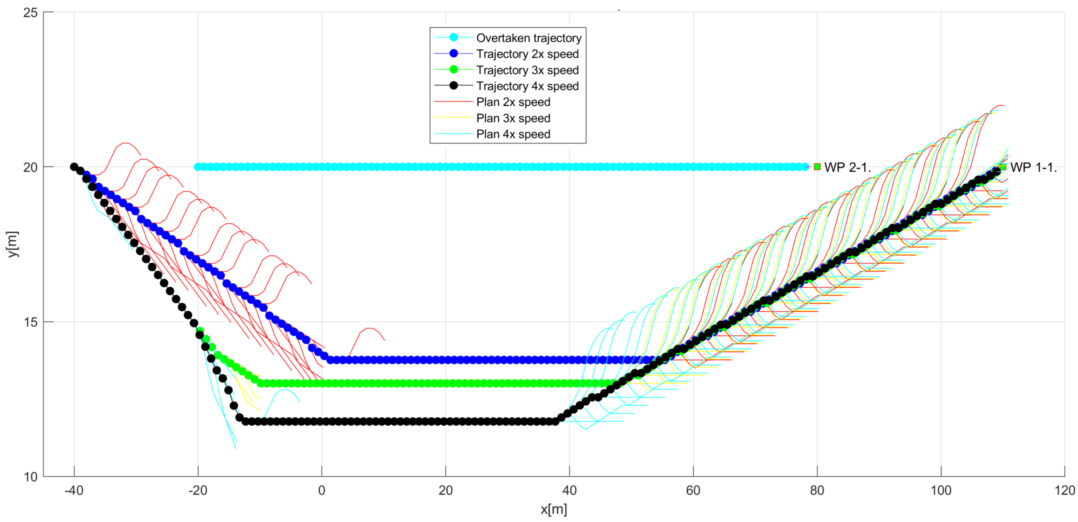


Figure 7.14: *Rule-based overtake* trajectories at a different speed.

Overtake Speed: Impact on Distance to Safety Margin Evolution *Safety margin* (red line) is set to *5 m*. It is obvious that *Faster UAS* will take down *Slower UAS* if there was not for an *Overtake maneuver*. The distance of *Faster UAS* to *Slower UAS* evolution is depending on *Speed difference*. *Inflection point* (closest point of two UAS) is reached sooner with *Higher speed*. *Safety margin performance* was measured for the *UTM performance time* in the interval $[0, 35]$ s and *Speed difference* of 2x (blue), 3x (green), 4x (black).

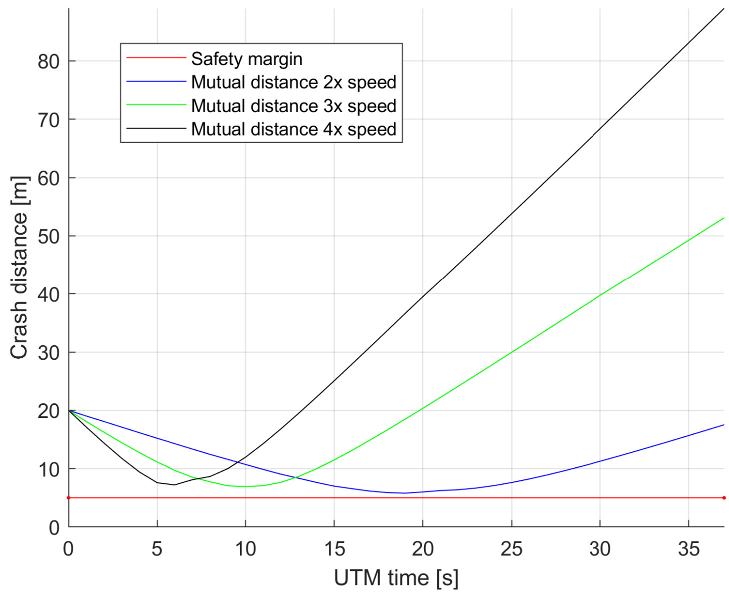


Figure 7.15: Overtake speed-dependent distance to safety margin evolution for *rule-based overtake scenario*.

Overtake Speed: Impact on Distance to Safety Margin Peaks There is summary table (tab. 7.16) for measurement of minimal and maximal values for *Distance to Safety Margin* over *UTM time* (fig.7.15). The minimal *Overtake Distance to Safety Margin* in 0.7991 m for 2x *Speed Difference*. The minimal *Overtake closest point reach time* is 7 s

for 4x *Speed Difference.*

For each *Speed difference* (2x, 3x, 4x), the *Well Clear Margin* (Safety Margin) was not reached by the *Faster UAS Body boundary.*

Speed diff.	Minimal distance	Minimal time	Maximal distance	Maximal time	Breach
2x	0.7991	20	48.8508	76	false
3x	1.9180	11	73.5336	51	false
4x	2.2154	7	84.0721	38	false

Table 7.16: Distance to safety margin peaks for various overtake speed in *rule-based overtake scenario.*

Path Tracking Performance: 2x Speed Performance was only evaluated for the case when *Faster/Slower UAS speed ratio* is $2x$. All waypoints are marked as green numbered *squares* with a number. Initial waypoint is marked as a green square with *S*. Reference trajectory is annotated as *green dashed line.* The *executed trajectory is annotated* as *solid blue line.*

Following observations can be made from path tracking (fig. 7.16):

1. *UAS 2 has the Right of Way* (fig. 7.16b) - *reference trajectory* and *executed trajectory* are identical.

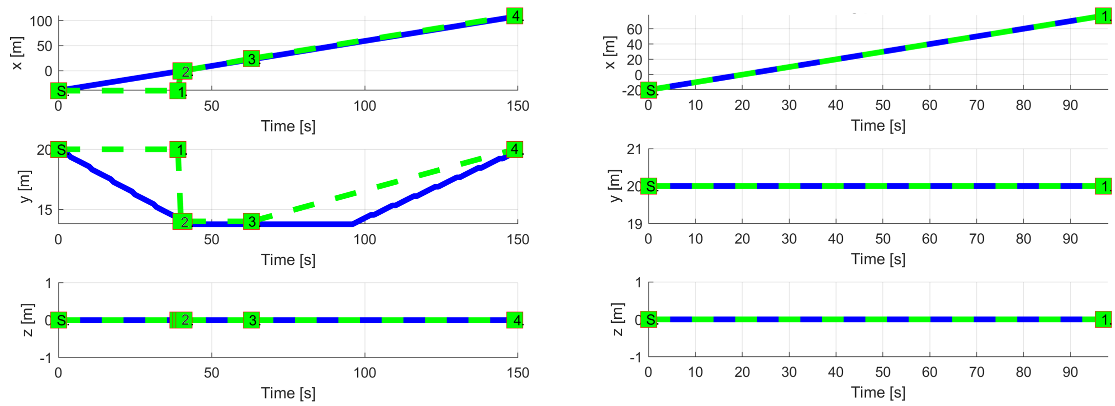
2. *UAS 1 is Overtaking* (fig. 7.16a) - the following waypoints are marked on reference trajectory:

   a. *Collision Point* ($\mathcal{WP}$ 1.) - this is not used for navigation, it is marking of *Collision Point.*

   b. *Divergence waypoint* ($\mathcal{WP}$ 2.) - there will *Faster UAS* navigate to avoid *Collision.*

   c. *Convergence waypoint* ($\mathcal{WP}$ 3.) - there will *Faster UAS* navigate to gain *Safe Return Distance.*

   d. *Original Goal Waypoint* ($\mathcal{WP}$ 4.) - there will *Faster UAS* continue until *original goal* is reached.



(a) UAS 1. (b) UAS 2.

Figure 7.16: Trajectory tracking for *rule-based overtake double speed* situation test case.

Path Tracking Deviations: 2x Speed Path tracking deviations (tab. 7.17) are interesting for an *Overtake Maneuver* performance.

Maximal deviation distance is for important waypoints: Divergence ($\mathcal{WP}$ 2.), Convergence ($\mathcal{WP}$ 3.) and Original Goal Waypoint ($\mathcal{WP}$ 4.), equal to 0 m. This is the *desired effect* for *Overtake maneuver*.

Collision point ($\mathcal{WP}$ 1.) is avoided at minimal distance 5.7991 m (tab. 7.16) and maximal distance 24.5 m (tab. 7.17).

Other *Speed Difference Ratios* yields similar results.

Param.	UAS 1				UAS 2
	$\mathcal{WP}_1$	$\mathcal{WP}_2$	$\mathcal{WP}_3$	$\mathcal{WP}_4$	$\mathcal{WP}_1$
	col.	div.	conv.	orig.	nav.
$\max\|x\|$	20	0	0	0	0
$\max\|y\|$	6	0	4	5	0
$\max\|z\|$	0	0	0	0	0
$\max dist.$	24.5	0	4	5	0

Table 7.17: Path tracking properties for *rule overtake 2x speed* scenario.

Computation Load: The *computation load* for *scenario* (fig.7.17) shows used time (y-axis) over decision frame (x-axis).

The load is minimal on both UAS because the rule calculates only the divergence (eq. **??**) and convergence (eq. **??**) waypoints.

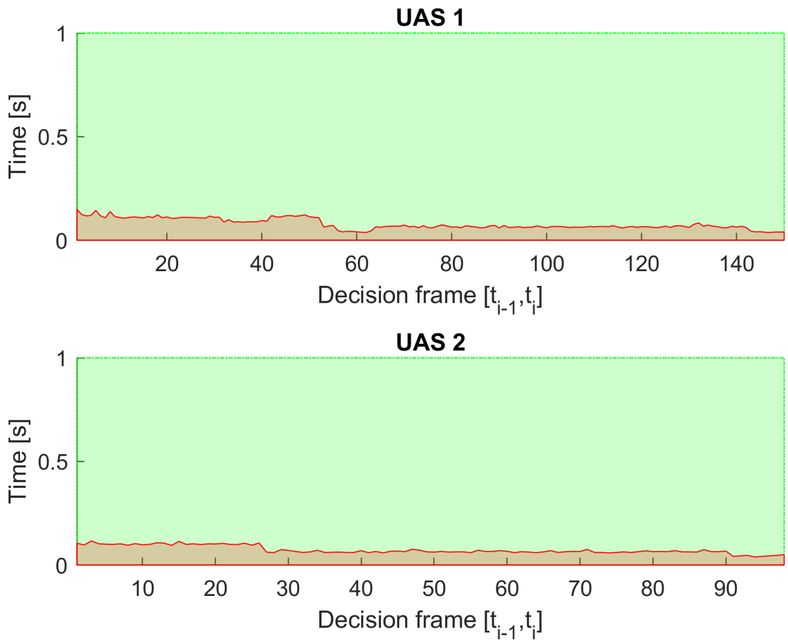


Figure 7.17: Computation time for *rule-based overtake* scenario.

Bibliography