

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	$[0, 20, 0]^T$	$[0^\circ, 0^\circ, 0^\circ]^T$	$[40, 20, 0]^T$
2	$[20, 0, 0]^T$	$[0^\circ, 0^\circ, 90^\circ]^T$	$[20, 40, 0]^T$

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*.

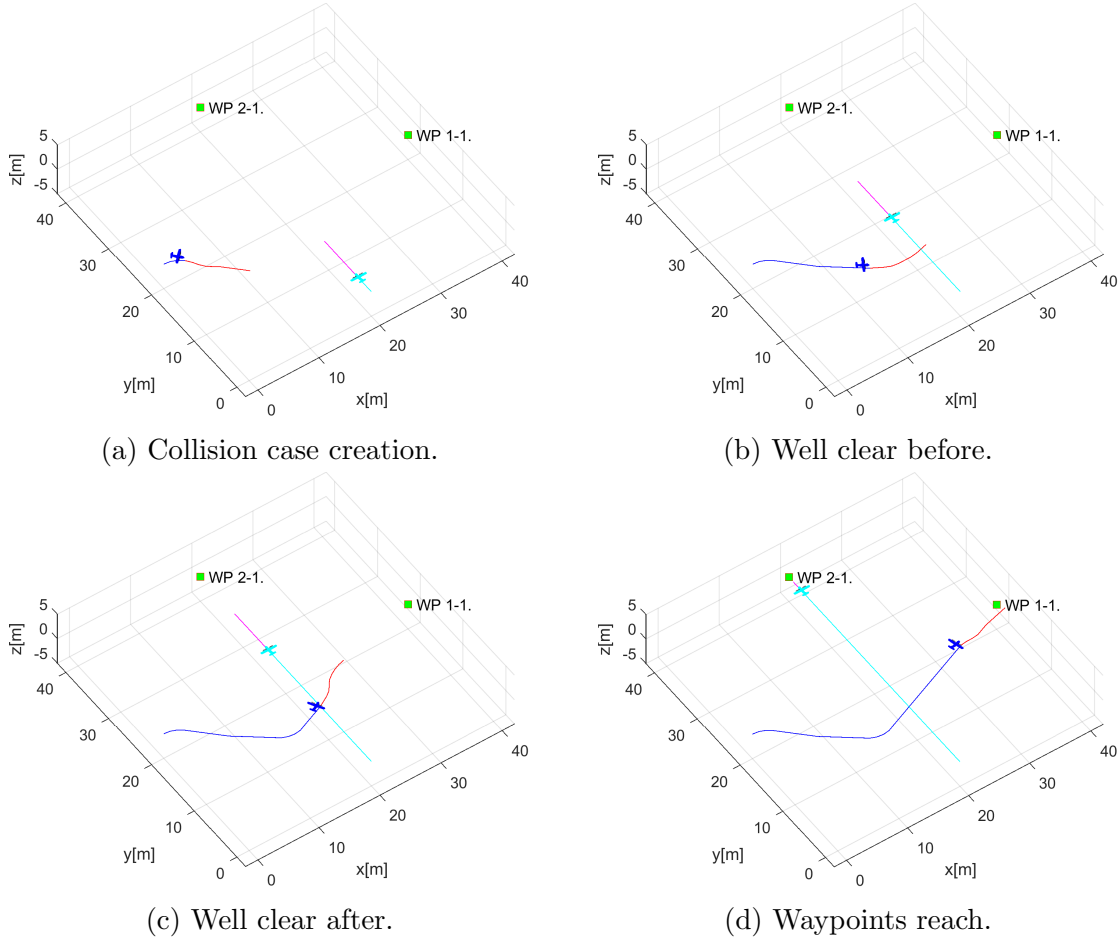


Figure 7.1: Test scenario for *Rule-based converging*.

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 $70^\circ \leq \text{angleOfApproach} < 130^\circ$.

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).

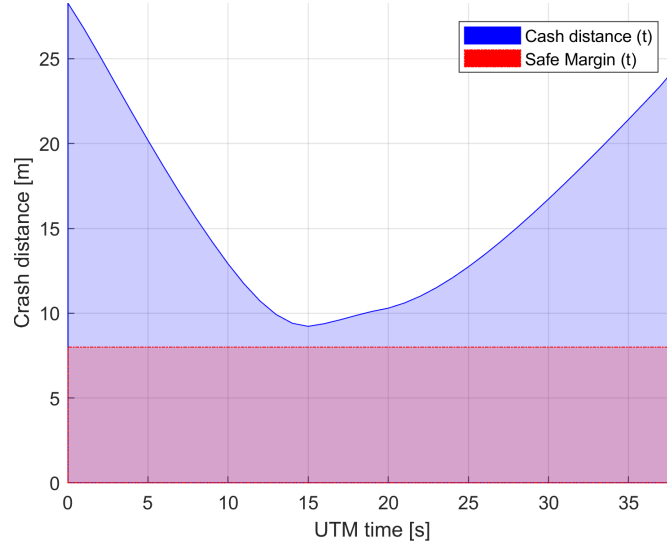


Figure 7.2: Distance to safety margin evolution for the *rule-based converging scenario*.

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*.

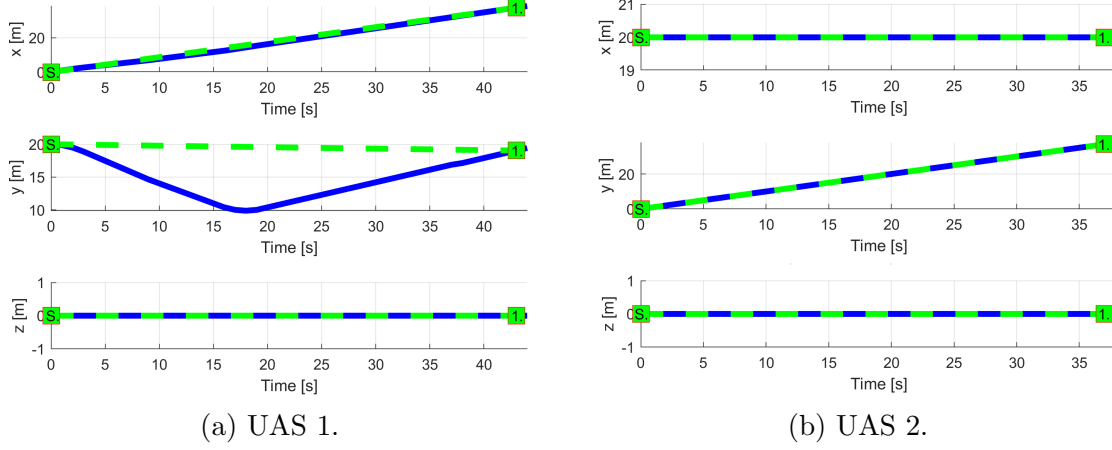


Figure 7.3: Trajectory tracking for Rule-based converging test case.

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.

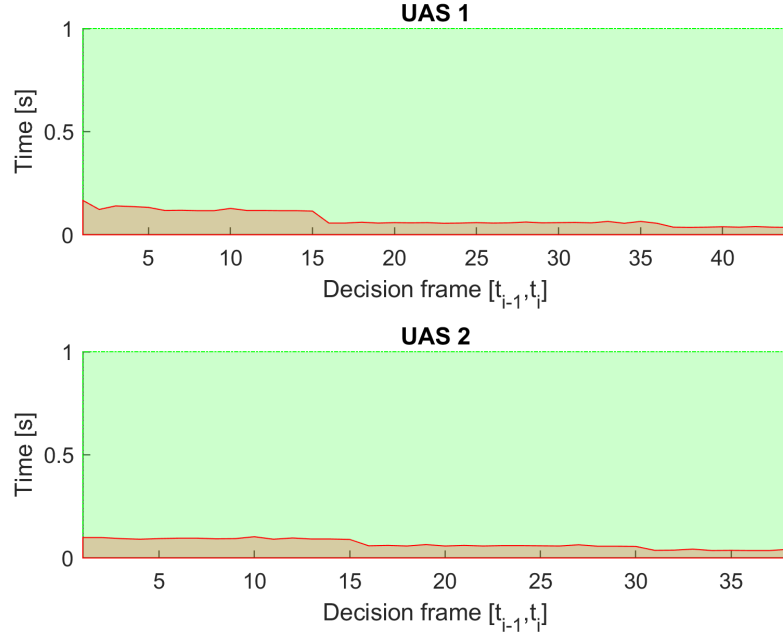
The minimal deviation distance was expected at the value of *safety margin* (8m). The maximal deviation was 10.22m which is acceptable due the space discretization, UAS dynamic, and, *dynamic decision time*.

Param.	UAS 1	UAS 2
	\mathcal{WP}_1	\mathcal{WP}_1
$\max x $	0	0
$\max y $	10.22	0
$\max z $	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	$[0, 20, 0]^T$	$[0^\circ, 0^\circ, 0^\circ]^T$	$[45, 20, 0]^T$
2	$[40, 20, 0]^T$	$[0^\circ, 0^\circ, 180^\circ]^T$	$[-5, 20, 0]^T$

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 \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 *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* 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.

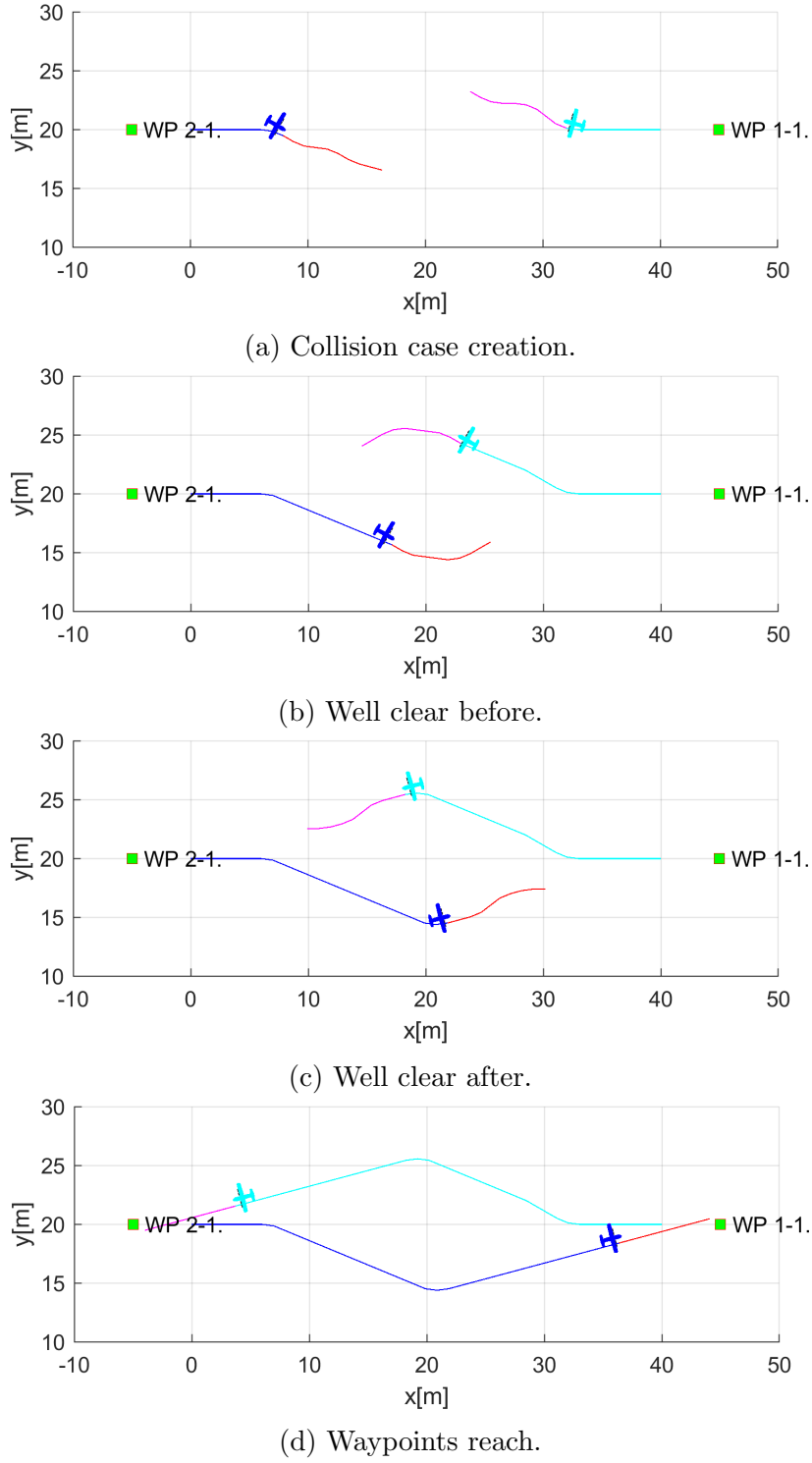


Figure 7.5: Test scenario for the *rule-based head-on approach* (virtual roundabout).

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 $130^\circ \leq \text{angle of Approach} \leq 180^\circ$ 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).

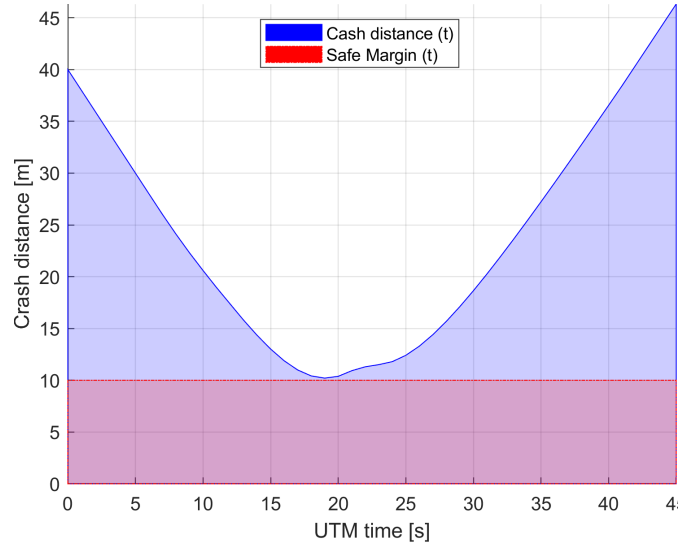


Figure 7.6: Distance to safety margin evolution for *rule-based head-on scenario*.

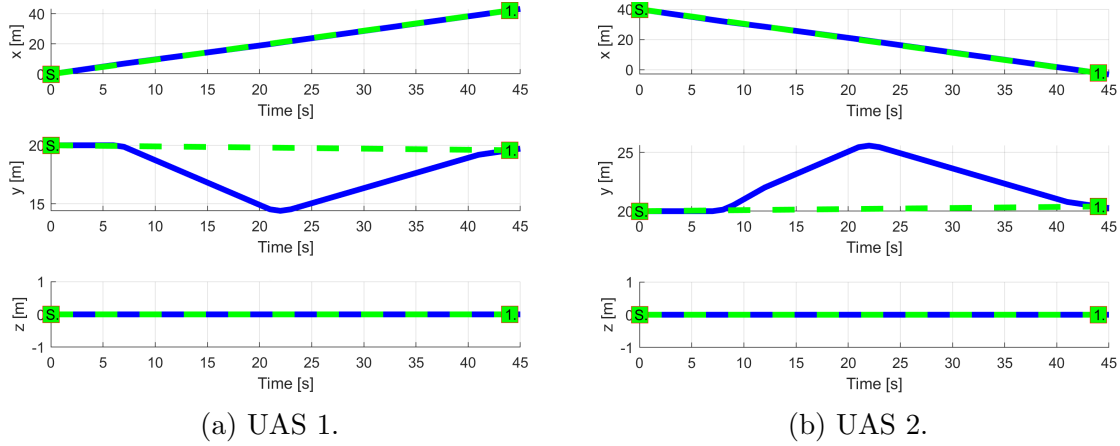
Distance to Safety Margin Peaks: Given by (tab. 7.7) represents the proximity on UAS mutual distance to *well clear condition* breach. The breach of *well clear condition* was not achieved. The *minimal distance to the safety margin* was 0.2084 m. The *maximal distance to safety margin* was 36.3253m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

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
	WP ₁	WP ₁
max $ x $	0	0
max $ y $	5.40	5.40
max $ z $	0	0
max <i>dist.</i>	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).

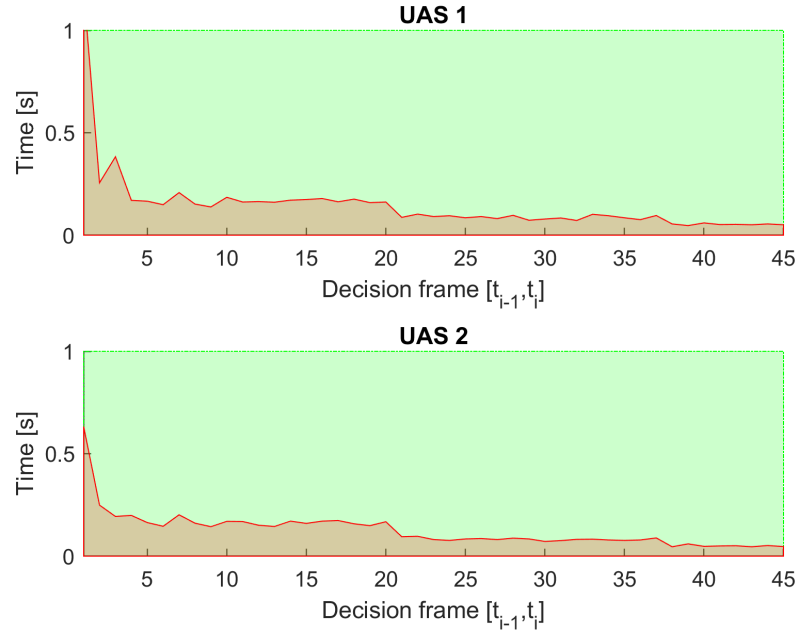


Figure 7.8: Computation time for *rule-based head-on* scenario.

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	$[0, 20, 0]^T$	$[0^\circ, 0^\circ, 0^\circ]^T$	$[45, 20, 0]^T$
2	$[40, 20, 0]^T$	$[0^\circ, 0^\circ, 180^\circ]^T$	$[-5, 20, 0]^T$
3	$[20, 0, 0]^T$	$[0^\circ, 0^\circ, 90^\circ]^T$	$[20, 45, 0]^T$
4	$[20, 40, 0]^T$	$[0^\circ, 0^\circ, -90^\circ]^T$	$[45, 20, 0]^T$

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*.

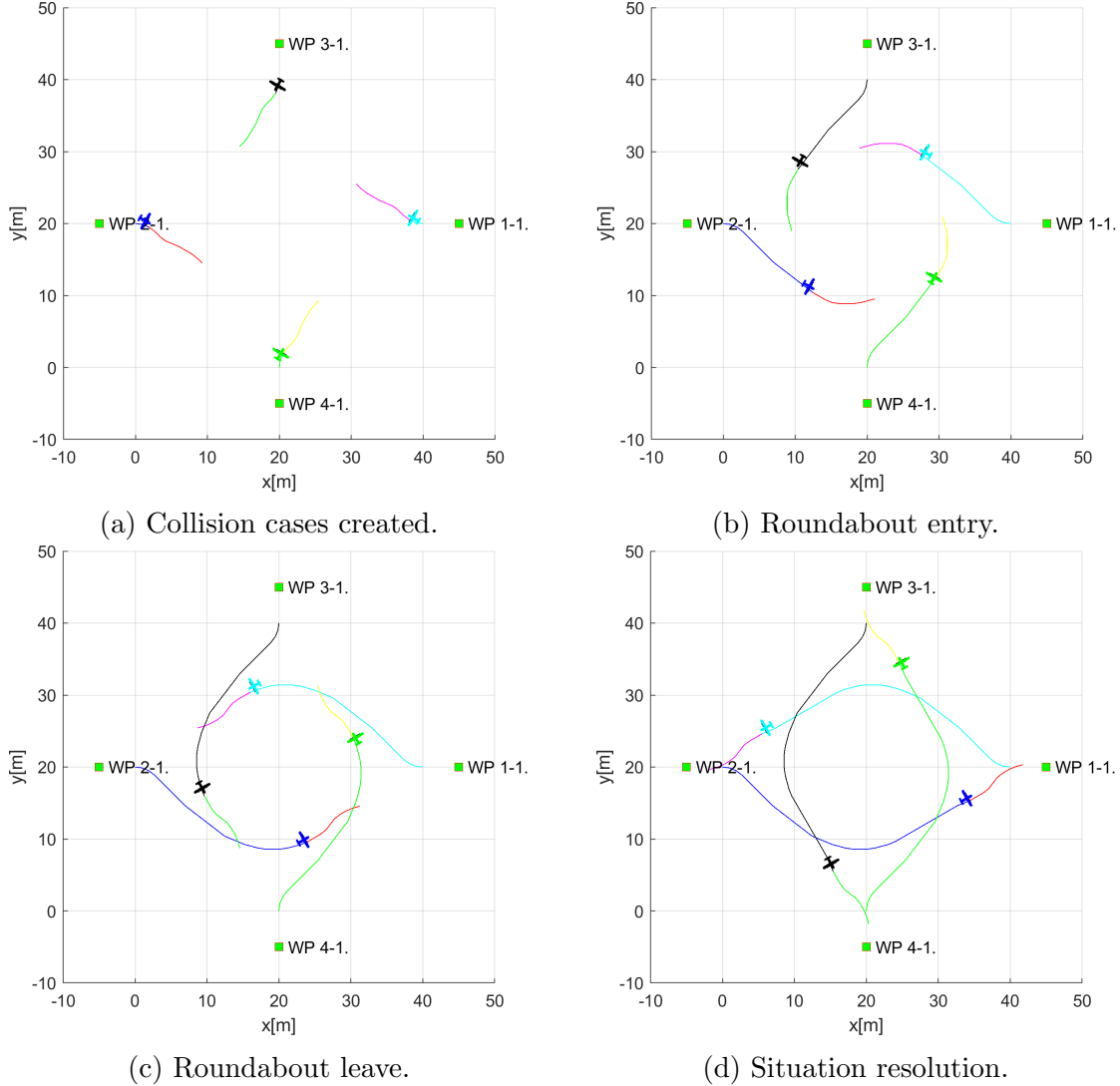


Figure 7.9: Test scenario for *rule-based mixed* situation with the *self-separation mode*.

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	
id	UAS	role	collision point	type		Margin	
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:

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

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.

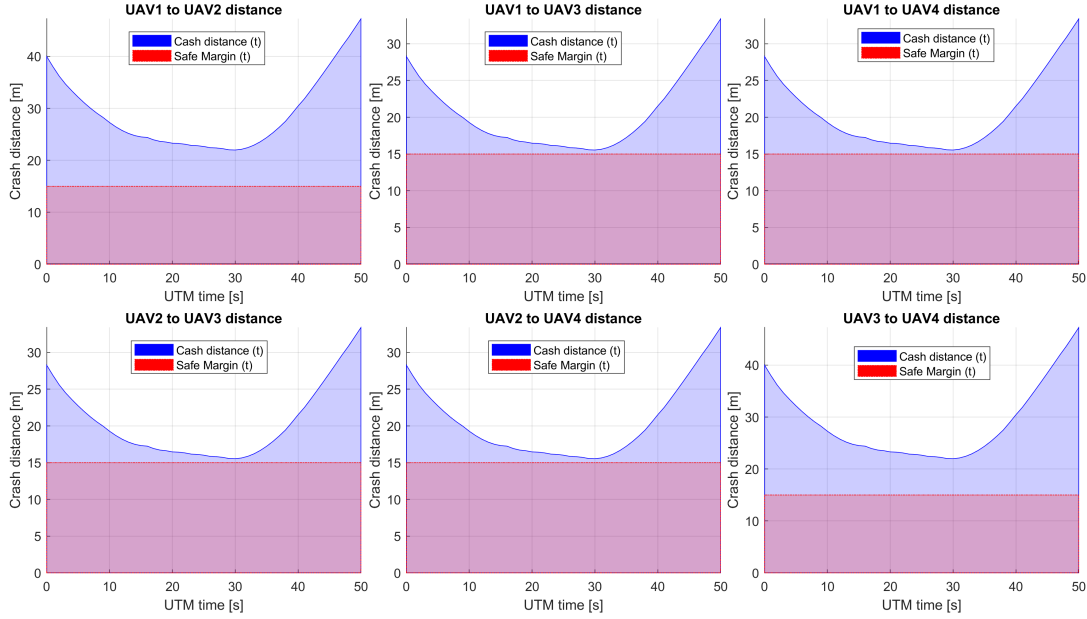


Figure 7.10: Distance to safety margin evolution for *rule-based mixed scenario*.

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* 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*.

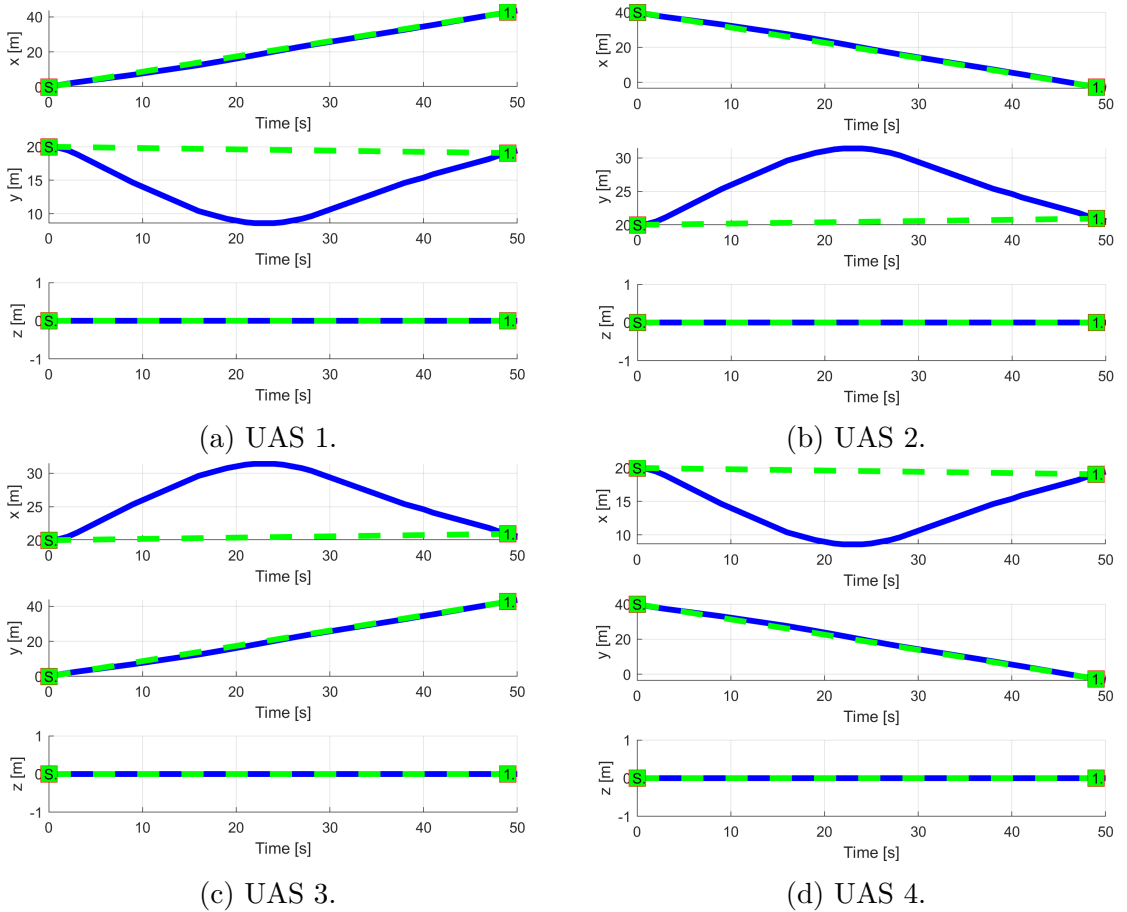


Figure 7.11: Trajectory tracking for *rule-based mixed* situation test case.

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 x $	0	0	11.40	11.40
$\max y $	11.40	11.40	0	0
$\max z $	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*.

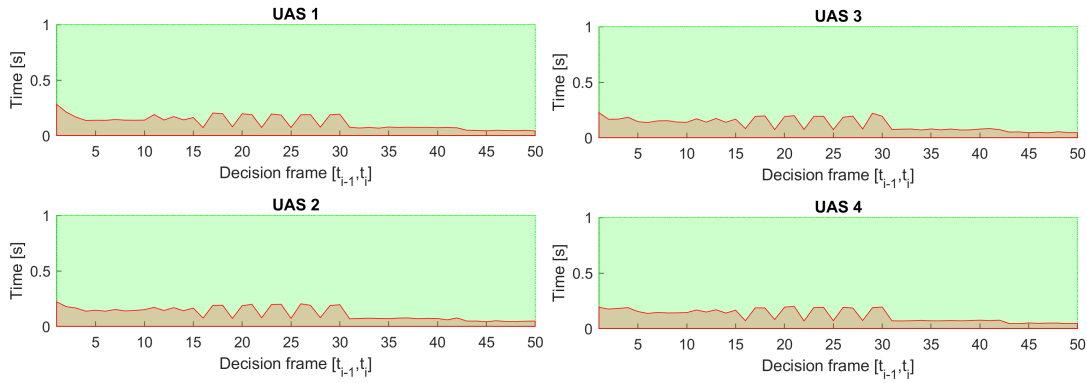


Figure 7.12: Computation time for *rule-based multiple* scenario.

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	$[-40, 20, 0]^T$	$[0^\circ, 0^\circ, 0^\circ]^T$	$[110, 20, 0]^T$
2	$[-20, 20, 0]^T$	$[0^\circ, 0^\circ, 0^\circ]^T$	$[80, 20, 0]^T$

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 \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*.

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 1st, Convergence 2nd).
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. ??).

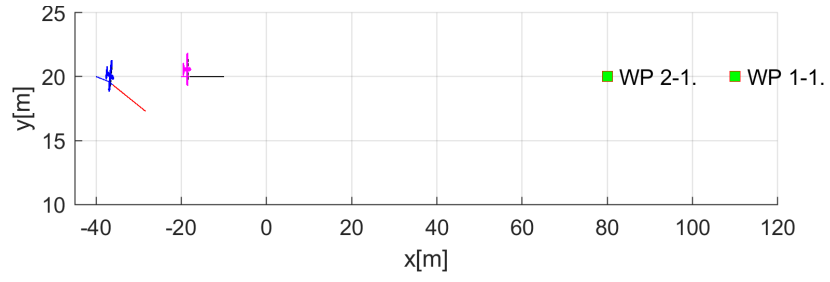
Simulation Run: Notable moments from the *simulation run* (fig. 7.13) are the following:

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*:

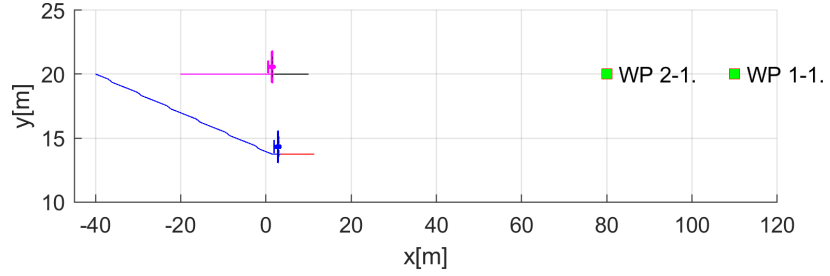
- a. *Divergence waypoint* at position $[0, 14, 0]^T$.
- b. *Convergence waypoint* at position $[24, 14, 0]^T$.

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

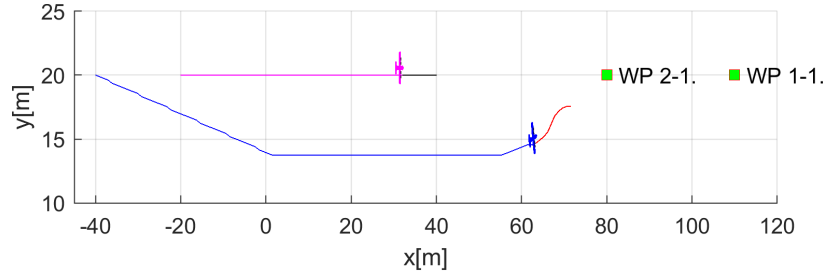
2. *Divergence waypoint reach* (fig. 7.13b) - *Faster UAS* (blue) successfully reached *Divergence Waypoint*, setting *Convergence Waypoint* as new *Goal waypoint*.
3. *Convergence waypoint reach* (fig. 7.13c) - *Faster UAS* (blue) successfully reached *Convergence Waypoint*, setting *Original Goal Waypoint*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



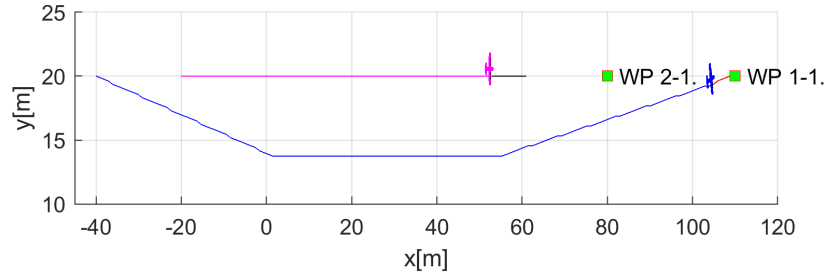
(a) Collision case creation.



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

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).

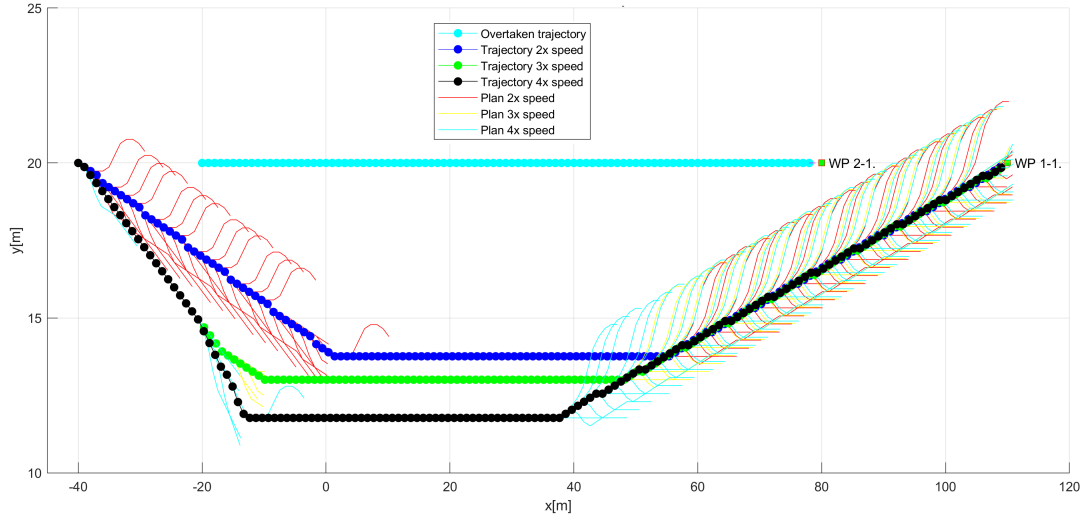


Figure 7.14: *Rule-based overtake trajectories at a different speed.*

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).

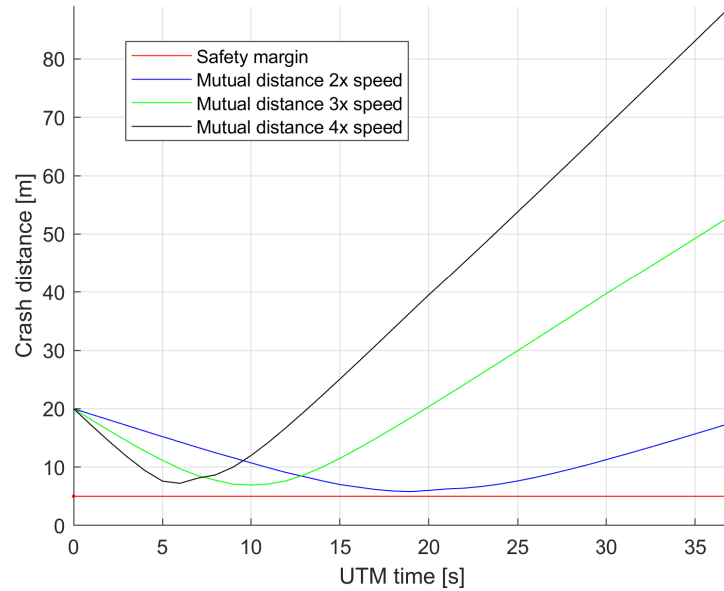


Figure 7.15: *Overtake speed-dependent distance to safety margin evolution for rule-based overtake scenario.*

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*.

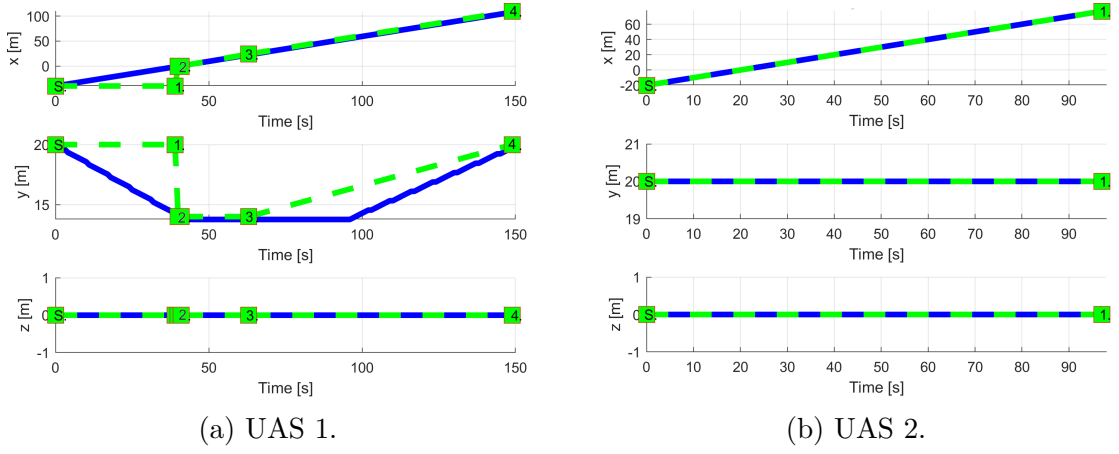
Speed diff.	Minimal		Maximal		Breach
	distance	time	distance	time	
2x	0.7991	20	48.8508	76	false
3x	1.9180	11	73.5336	51	false
4x	2.2154	7	84.0721	38	false

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* (WP 1.) - this is not used for navigation, it is marking of *Collision Point*.
 - b. *Divergence waypoint* (WP 2.) - there will *Faster UAS* navigate to avoid *Collision*.
 - c. *Convergence waypoint* (WP 3.) - there will *Faster UAS* navigate to gain *Safe Return Distance*.
 - d. *Original Goal Waypoint* (WP 4.) - there will *Faster UAS* continue until *original goal* is reached.

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 (WP 2.), Convergence (WP 3.) and Original Goal Waypoint (WP 4.), equal to 0 m. This is the *desired effect* for *Overtake maneuver*.

Collision point (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
	WP ₁	WP ₂	WP ₃	WP ₄	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 <i>dist.</i>	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.

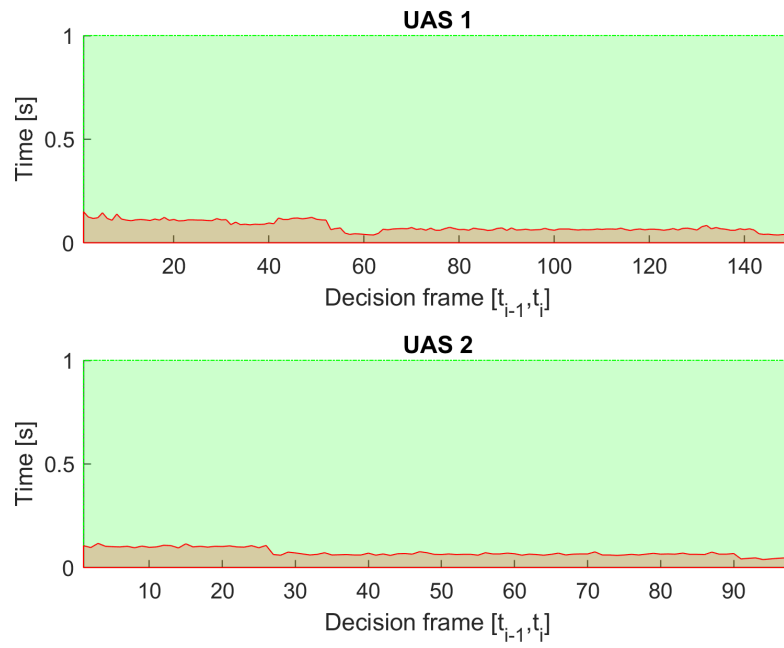


Figure 7.17: Computation time for *rule-based overtake* scenario.

Bibliography