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A Methodology Of Virtual Testing and Certification Of Aircraft Flight Safety Performance In Complex Situations

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Research Task Formulation

Problem

'Theoretically improbable' complex (multi-factor) situations do occur in flight test and operation often leading to an incident/accident. These anomalous multi-factor cases are difficult to identify in advance – during the design, test & certification/evaluation phases – due to combinatorial, technical, time and budget constraints.

Solution Approach

'Knowledge is Power'. The 'operator (pilot, automaton) – aircraft/ project – operational environment' system model is employed as a 'knowledge generator' of complex flight situation domains. A broad set of realistic multi-factor scenarios is designed, virtually tested and assessed in advance using fast-time 'what-if' modeling and simulation (M&S) experiments.

Overall Goal

Demonstrate an affordable and easy-to-use methodology of a 'bird's eye view' level M&S, depiction, analysis and prediction of the aircraft safety performance in complex conditions.

Main Tasks

Develop theoretical framework for planning and examination of a broad domain of potentially unsafe multi-factor situations using the system model. Design anthropomorphic maps to represent M&S knowledge to designers, flight test engineers/ pilots. Demonstrate feasibility of knowledge-centered M&S based methodology for flight safety prediction and assessment.

Methods & Tools

Experimental and computational aircraft aerodynamics, flight dynamics, situational control, complex flight domain theory, mathematical modeling, numeric techniques, simulation experiment, artificial intelligence (AI), graph theory, dynamic data structures, computer graphics, VATES (Virtual Autonomous Test & Evaluation Simulator, v. 7) proprietary software tool, PC Pentium-IV, MS Windows, MS Office, Pfe, MAGE, etc.

→ Classic techniques + modern techniques = new analytical potential for affordable, fast-time analysis of the 'operator (pilot, automaton) – aircraft/ project – operational environment' system safety properties in advance.

Micro- and Macro- Structural Models Of a Complex Flight Situation Domain

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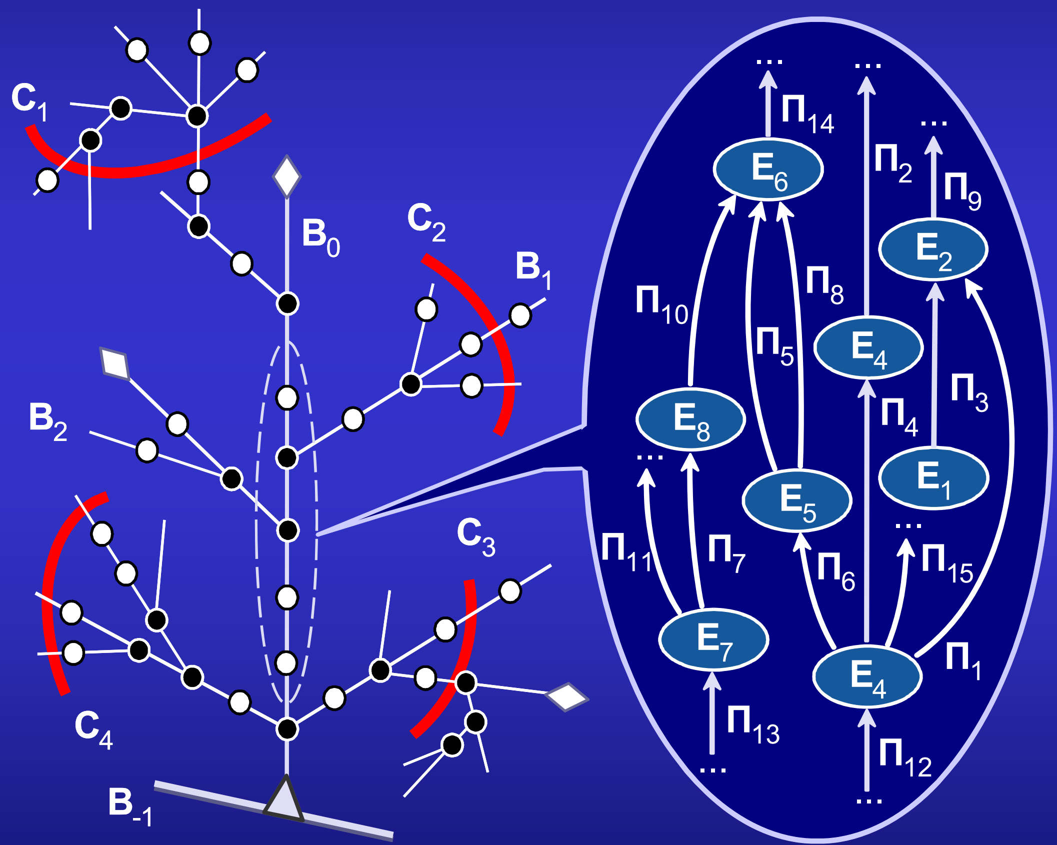
Situational tree -network of flight

Flight situation scenario

Elementary situation (E_i, $Π_j$, E_k)



Macro-structure of flight

Micro-structure of flight

Legend:

E_i - flight event; $Π_j$ - flight process; C_m - fuzzy constraint of flight; ● - reference state; ● - "bud" type state; ◇ - target state ("leaf"); ▲ - source state ("root"); B_{-1} - parent branch; B_0 - main branch ("trunk") basic flight scenario ; B_n - n^{th} order derivative branch (non standard scenario with n factors , n = 1, 2, …)

➔ Micro- and macro-structures of flight are generalized and interconnected knowledge models.

Fractal Model of Ideal Process of Human Pilot's Experience Growth In Long-Term Memory

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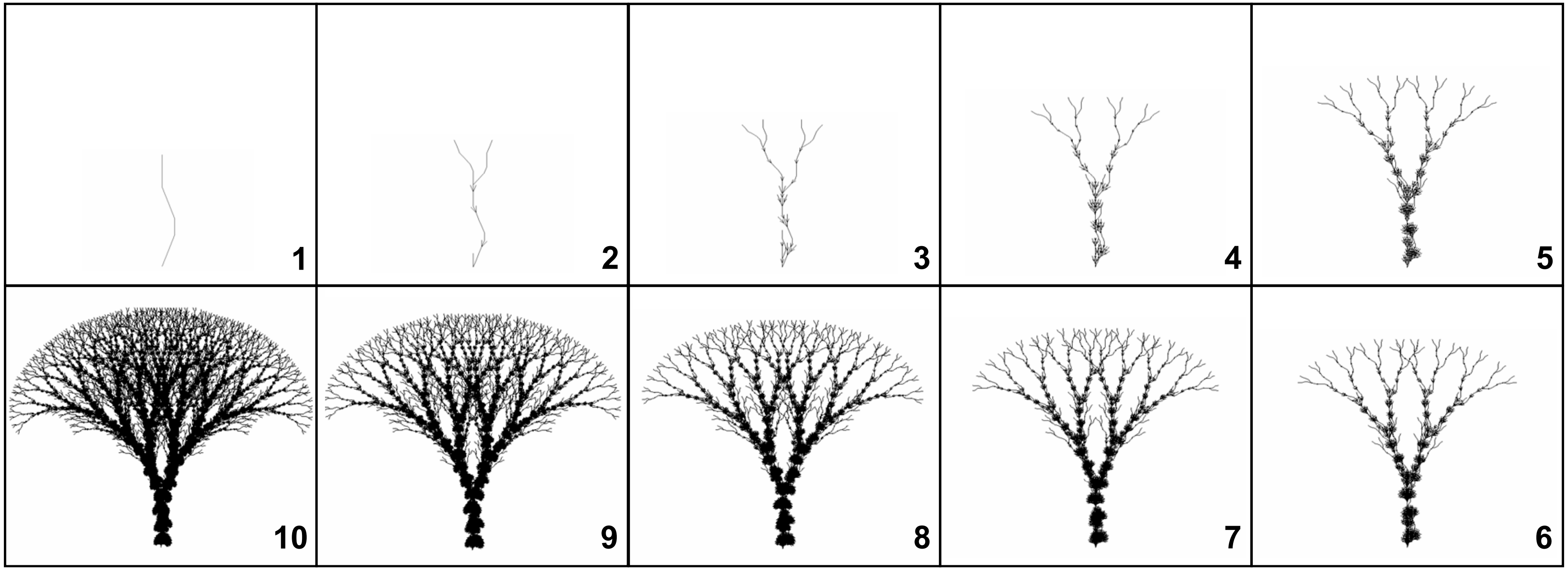

Legend: Characteristic levels of piloting expertise: $k \in \{1, 2, 3\}$ – experience of a student pilot, $k \in \{8, 9, 10\}$ – experience of a professional pilot, ace, or test pilot, $k \in \{4, \ldots, 7\}$ – interim (immature) states of experience.

➔ The most valuable asset of an expert pilot (a perfect automaton) is the reliability and comprehensiveness of his/her (its) knowledge of the system behavior under multi-factor (complex, non-standard) flight conditions. Though this expertise is very difficult to gain, it is of critical importance for timely prediction, avoidance and safe resolution of 'chain reaction' type emergencies.

Natural Tree Analogy of Main Defects Of Human Pilot's Situational 'Knowledge Base'

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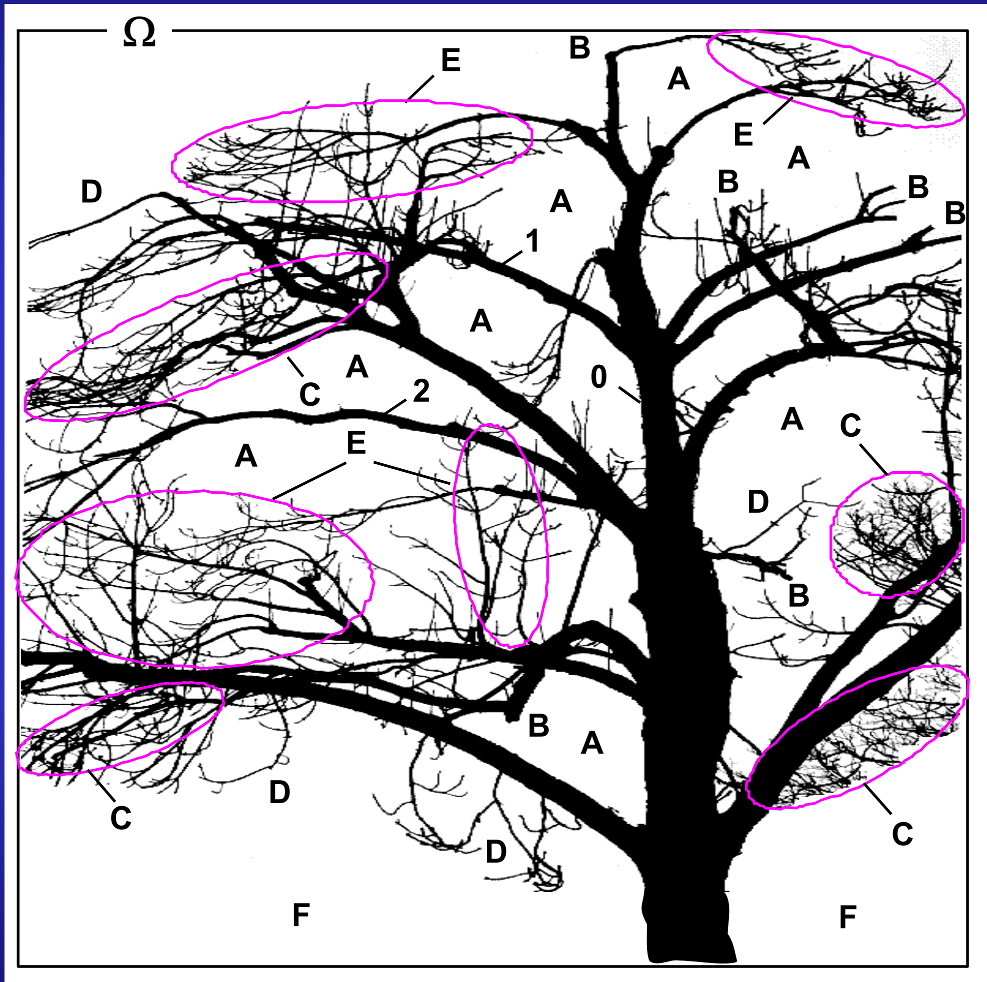

Legend:

	Characteristic zone of a pilot's situational knowledge base	Natural tree analogy
Ω	Space of possible complex flight situation scenarios	Space available for tree growth
0	Basic (standard/non-standard) flight situation scenario	Tree's trunk
1	One-factor non-standard flight situation scenario	First-order derivative branch
2	Two-factor non-standard flight situation scenario	Second-order derivative branch
A	**Missing knowledge**	**Absent but possible branching**
B	**Forgotten or shadowed knowledge**	**Dry or broken branches**
C	**Unsystematic knowledge**	**Excessive, chaotic branching**
D	**Fragmentary knowledge**	**Insufficient, sparse branching**
E	Systematic knowledge	Optimally dense branching
F	Physically unattainable flight situation scenarios	A sub-domain where branching is impossible

Defects to be backed up by means of M&S

A, **B**,**C**, **D** – main defect types of a human pilot's situational knowledge.

➔ Lack of systematic theoretical and practical training (thorough design and testing) under multi-factor conditions may result in structural disparity of a human pilot's (automaton's) internal 'situational tree' of flight.

Safety Palette. Fuzzy Constraint

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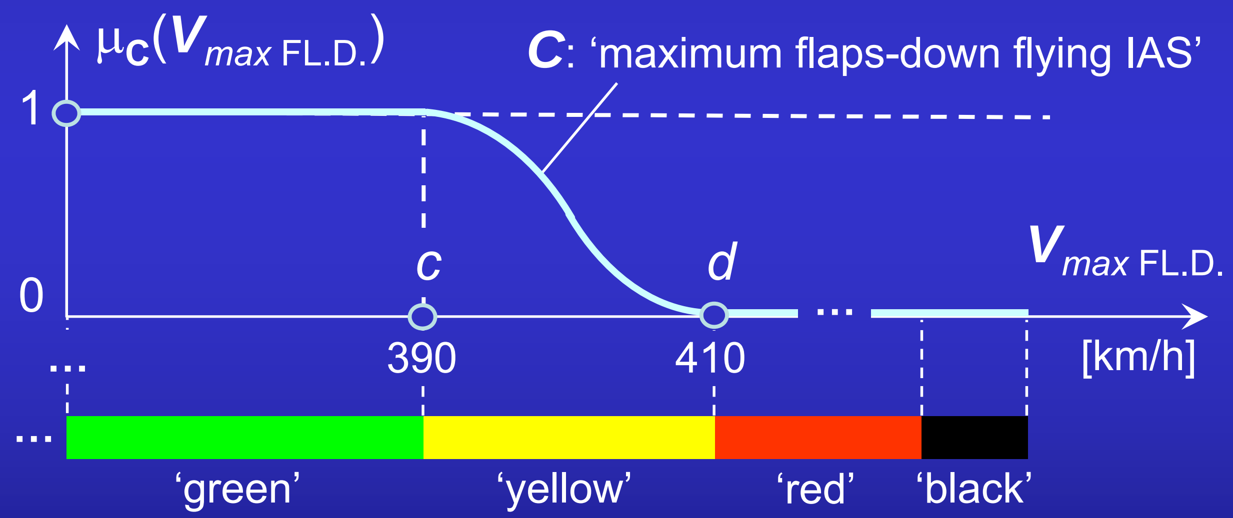
Safety Palette

- green ('norm'), ξ_G
- yellow/ amber ('attention'), ξ_Y
- red ('danger'), ξ_R
- black ('catastrophe'), ξ_B
- grey/white ('uncertainty'), ξ_W

➔ Color is natural and, perhaps, the most effective and economic medium for communicating safety-related information to/ from an operator or expert

Fuzzy Constraint (Example)



Legend: ***c***, ***d*** – characteristic points of the carrier of the fuzzy set-constraint ***C***, $\mu_C(x)$ – L.Zadeh membership function

➔ Operational constraints, especially under multi-factor conditions of flight, are not known precisely – they are inherently 'fuzzy'. The notions of Fuzzy Constraint (first introduced by L.A. Zadeh) and Safety Palette are employed for approximate measurement of the compatibility of current system states (i.e. measured at time instants *t*) with operational constraints for key System Model Variables.

Partial Safety Spectra. Integral Safety Spectrum of a Flight Situation

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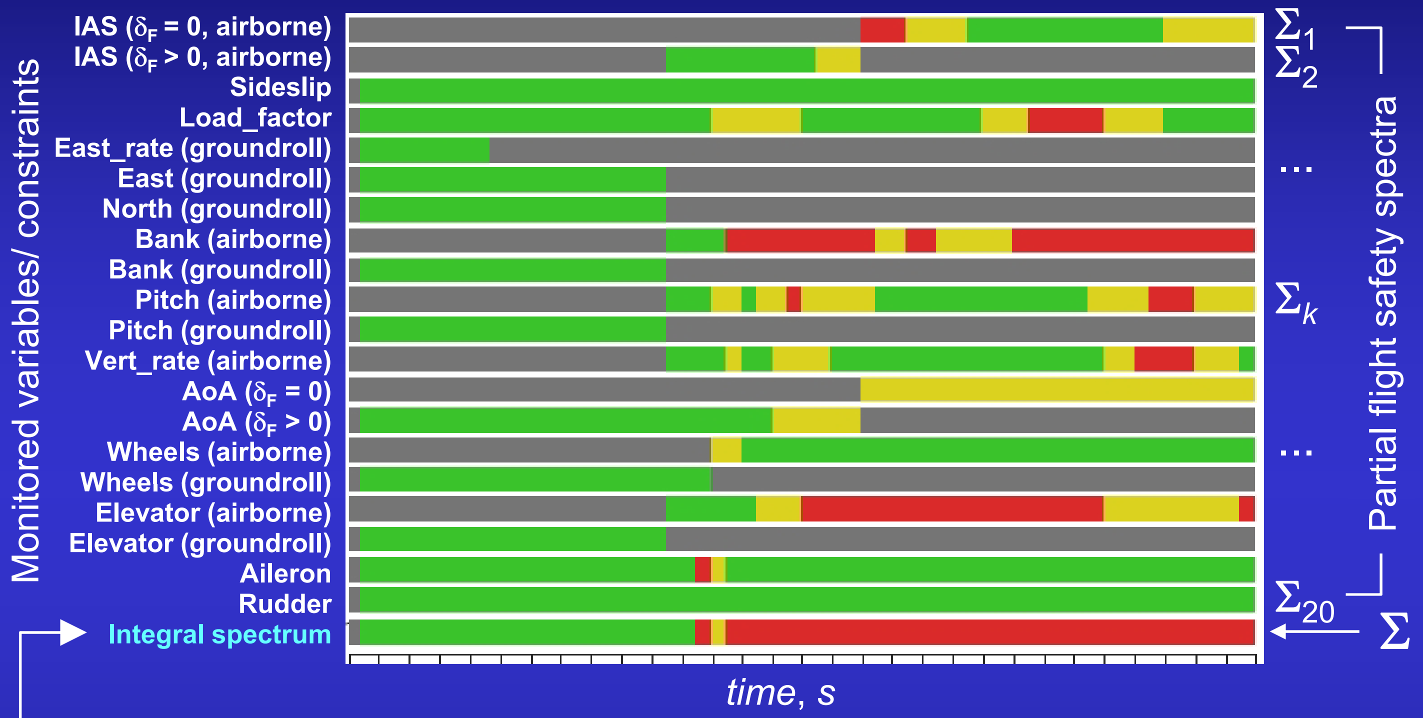

Legend: Σ_k – partial safety spectrum for variable x_k, k = 1, …, p; p – total number of monitored constraints/ variables, p = 20. Σ – integral safety spectrum; t – flight time; ξ_i – color from safety palette, $i \in$ {B (black), R (red), Y (yellow), G (green),…}; < – 'colder than' operation for comparing two safety colors; *max* – operation of selecting the 'hottest' color at time instant t; || - operation of safety colors concatenation in Σ; $[t_*; t^*]$ – examined flight time interval; Δ – spectrum construction time step.

- green ('norm'), ξ_G
- yellow ('attention'), ξ_Y
- red ('danger'), ξ_R
- black ('catastrophe'), ξ_B
- gray/white ('uncertainty'), ξ_W

Integral Safety Spectrum Calculation Algorithm:

$$(\forall t)\ (t \in [t_*; t^*])\ (\exists \xi(x_k(t))\ (\xi(x_k(t)) \in \{\xi_W, \xi_G, \xi_Y, \xi_R, \xi_B, \dots\} \wedge (\xi_W < \xi_G < \xi_Y < \xi_R < \xi_B))$$

$$(\xi(t) = max\ \xi(x_k(t)),\ k = 1, \dots, p) \Rightarrow (\xi(t) \in \Sigma \wedge \Sigma = \xi(t_*) \,||\, \xi(t_*+\Delta) \,||\, \xi(t_*+2\Delta) \,||\, \dots \,||\, \xi(t^*))$$

➔ After having measured current safety levels for all monitored variables x_k at all time instants of a flight situation, a family of Partial Safety Spectra Σ_k, k = 1, …, p, and an Integral Safety Spectrum Σ are obtained. The sources of flight data are: computer M&S, manned flight simulation, test and operational flight records.

Safety Classification Categories

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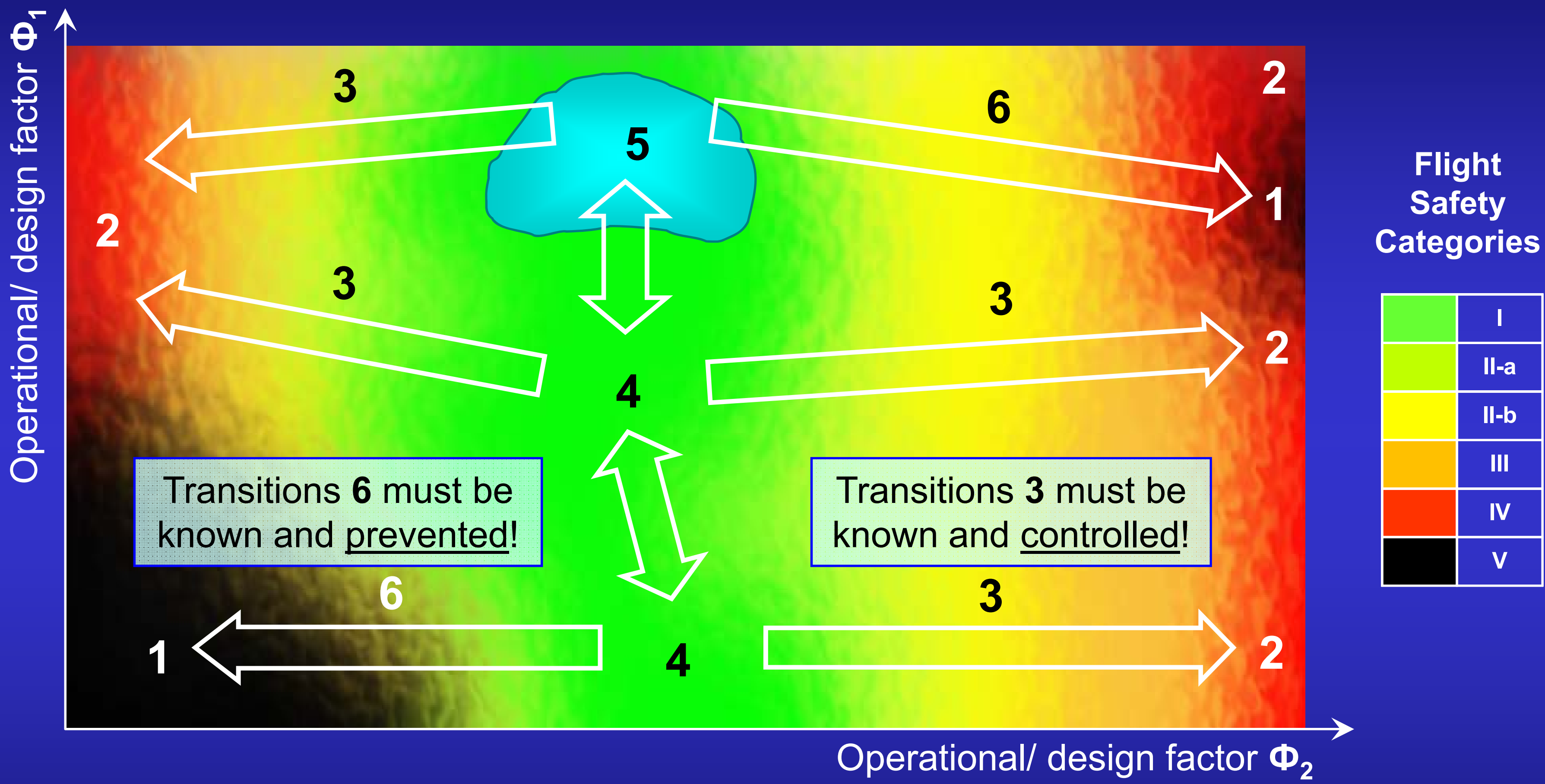
Flight Safety Category			Flight Situation Classification Criterion
Color	Code	Name	
Green	**I**	Safe	The system state resides mainly inside the 'green' zone. As a maximum, the system state may stay, for a *short time*, in close proximity to operational constraints, i.e. inside the 'amber' zone, but must leave it by the end of the flight situation
Light green	**II-a**	Conditionally Safe – a	As a maximum, the system state may stay for a *medium time* in close proximity to operational constraints, i.e. inside the 'amber' zone
Yellow	**II-b**	Conditionally Safe – b	As a maximum, the system state may stay for a *long time* in close proximity to operational constraints, i.e. inside the 'amber' zone
Orange	**III**	Potentially Unsafe	As a maximum, the system state may violate operational constraints, i.e. enter the 'red' zone, for a *short or medium time*, but must leave it by the end of the situation
Red	**IV**	Dangerous (Prohibited)	As a maximum, the system state may stay beyond operational constraints, i.e. inside the 'red' zone, for a *long time* or till the end of the flight situation
Black	**V**	Catastrophic ('Chain Reaction')	There is at least one (for a *short time*) occurrence of a 'black' violation of any operational constraint

➔ In order to measure the vehicle's safety performance in some flight situation as a whole, a generalized 'safety ruler' consisting of five Safety Classification Categories **I**, …, **V** is employed. Why five? – Because experts cannot reliably recognize and use more than 5-10 gradations of a complex, difficult-to-formalize system-level property (e.g.: Cooper-Harper scale). 'Light green' and 'orange' colors are added to Safety Palette to denote interim Categories **II-a** and **III**, respectively.

Flight Safety 'Topology'



➔ In general, the following characteristic objects can be defined within the Flight Safety 'Topology':

1 '**Abyss**' (catastrophe)
2 '**Hill**' (danger)
3 '**Slope**' (reversible state transitions)

4 '**Valley**' (standard safety, norm)
5 '**Lake**' (maximum safety, optimum)
6 '**Precipice**' (abrupt, irreversible state transitions,'chain reaction')

Basic Flight Scenarios

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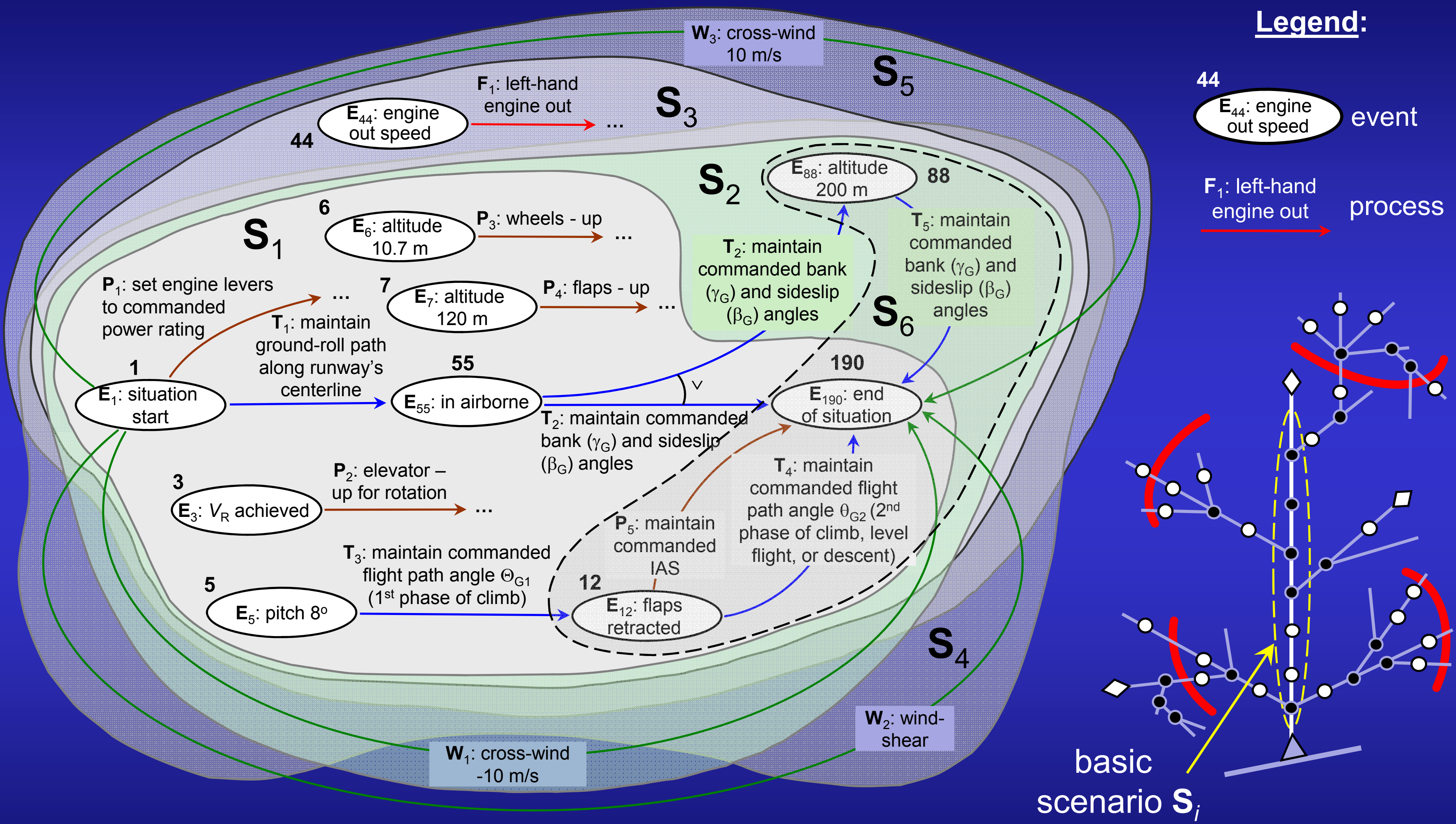
S_1	Normal takeoff, benign weather	Normal takeoff, benign weather (ground-roll, lift-off, and initial climb maintaining commanded flight path and bank angles)
S_2	Normal takeoff, cross-wind	Normal takeoff, cross-wind conditions and slippery runway (ground-roll, lift-off, and initial climb maintaining commanded flight path and bank angles)
S_3	Continued takeoff, one engine out	Continued takeoff, one engine out at V_{EF} (ground-roll, lift-off, and initial climb maintaining commanded flight path and bank angles)
S_4	Normal takeoff, wind-shear	Normal takeoff, wind-shear conditions, (ground-roll, lift-off, and initial climb maintaining commanded flight path and bank angles)
S_5	Continued takeoff, one engine out, cross-wind	Continued takeoff, cross-wind conditions and one engine out at V_{EF} (ground-roll, lift-off, and initial climb maintaining commanded flight path and bank angles)
S_6	Low-altitude climb, level flight or descent	Low-altitude climb, level flight or descent in the presence of urban infra-structure obstacles, maintaining commanded flight path and bank angles

➔ Basic (Baseline) Scenario $\mathbf{S}_i$ is a plan of some 'central' situation (i.e., the situational tree's trunk) – be it standard or non-standard one. Its variations – derivative cases – are to be virtually tested in M&S experiments. The goal is to evaluate the effects of selected key operational/ design factors and operational/ design hypotheses on flight safety. The sources of data for planning basic scenarios are: airworthiness requirements (АП, FAR, JAR), flight test data/ programs, ACs, Pilot's Manuals, actual flight data records, flight accident/ incident statistics.

Joint Graph of Basic Flight Scenarios



➔ A Flight Situation Scenario is depicted as a directed graph. Scenario graphs are clear and compact maps of flight situation content and logic. Scenarios S_1, …, S_6 are structurally close. They can be easily modified.

Operational Factors for Testing In M&S Experiments (Examples)

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Φ_i	Name	x_i	Sub-domains of tested values, $\Omega(\Phi_i)$	Unit
Φ_1	Longitudinal C.G. position	$\bar{x}_{CG}$	{23.5, 24.5, …, 28.5} ∨ {23.5} ∨ {28.5}	%
Φ_2	Rotation airspeed	V_R	{150, 160, …, 250} ∨ {170, 200, 230}	km/h
Φ_3	Elevator increment for rotation	$\Delta\delta_e$	{-15, -14, …, -5}	deg.
Φ_4	'Wheels – runway surface' adhesion factor	μ	{0.2 ('water covered'), 0.3 ('wet'), …, 0.8 ('dry')}	-
Φ_5	Cross-wind velocity	W_{yg}	{-20, -15, …, +20} ∨ {-18, -15, …, +18}	m/s
Φ_6	'Flaps-up' start altitude	H_{FL}	{40, 60, …, 120} ∨ {20, 30, …, 140}	m
Φ_7	Commanded flight path angle (1st phase)	θ_{G1}	{2, 4, …, 14} ∨ {1, 2, …, 7} ∨ {2, 3, …, 14} ∨ {2, 4, …, 20}	deg.
Φ_8	Commanded flight path angle (2nd phase)	θ_{G2}	{0, 2, …, 12} ∨ {0, 1, …, 12} ∨ {-12, -10, …, 24}	deg.
Φ_9	Wind-shear intensity	k_W	{1, 1.2, …, 2} ∨ {1} ∨ {1.5}	-
Φ_{10}	Engines power rating at takeoff	k_P	{60, 80, 100} ∨ {70, 100}	-
Φ_{11}	Commanded bank angle	γ_G	{-45, -37.5, …, +45} ∨ {-30, -15, …, +30}	deg.
Φ_{12}	'Engine out' airspeed	V_{EF}	{100, 115, …, 205}	km/h
Φ_{13}	Left-hand engine out or operative at V_{EF}	ξ_{LHE}	{0, 1}	-

Legend: Φ_7 - commanded flight path angle (1st phase of climb); Φ_8 - commanded flight path angle (2nd phase: climb, level flight or descent); Φ_{10} - engines power rating (throttles setting) at takeoff; Φ_{11} - commanded bank angle (climb or descent); $k_W = 1 \Rightarrow$ 'strong' wind-shear, …, $k_W = 1.5 \Rightarrow$ 'very strong' wind-shear, …, $k_W = 2 \Rightarrow$ hurricane-type wind-shear.

➔ Operational /Design Factors are modified or new events and/or processes, which – after having been added to a basic scenario – can improve or worsen the aircraft's safety performance. There are three groups of operational factors: 'operator', 'aircraft' and 'external environment'. The sources of information on operational factors are: national airworthiness requirements, FMEA, statistics on flight operations, accidents and incidents.

Design Field of Operational Hypotheses

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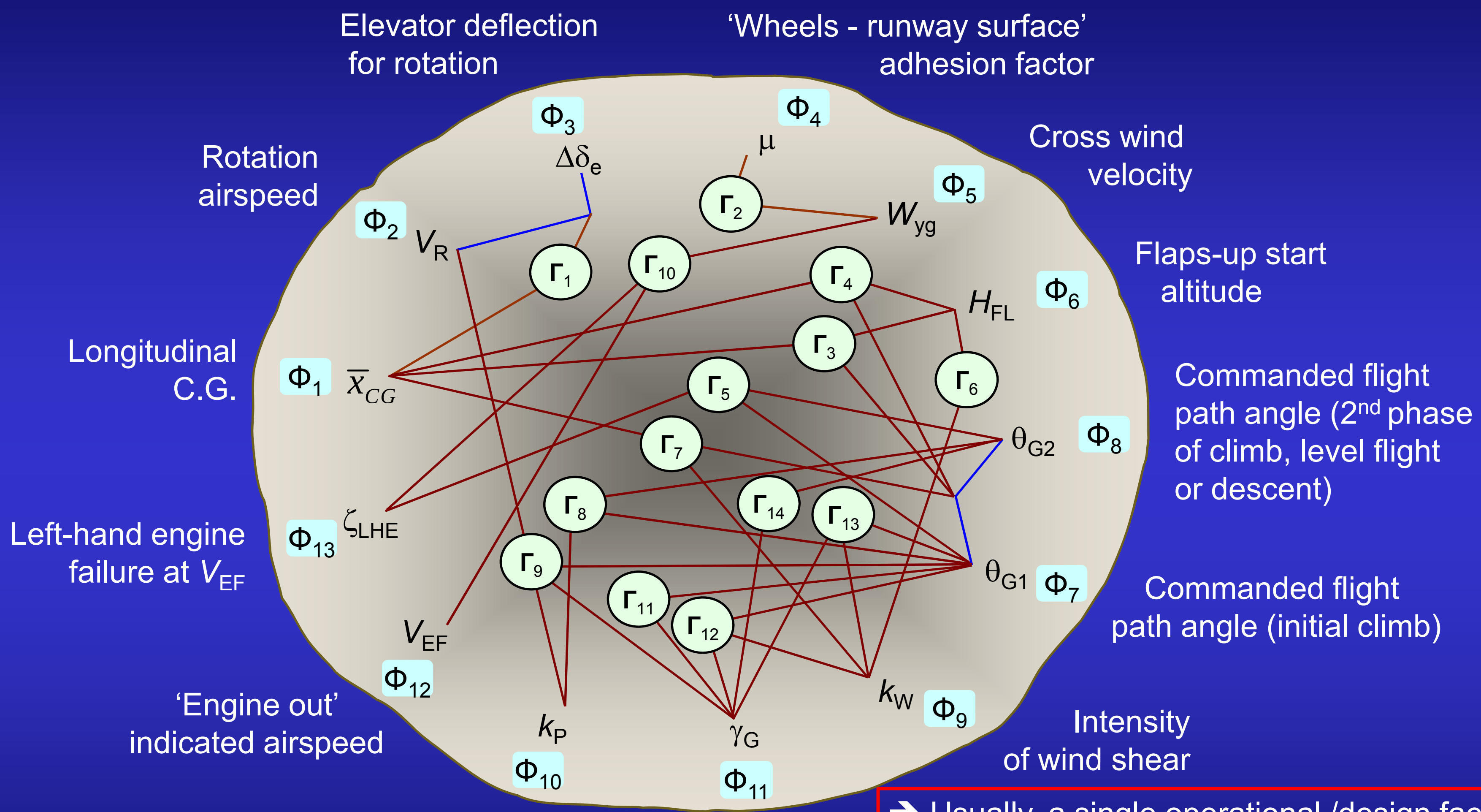

Engines power rating at takeoff

Commanded bank angle

Legend:

Γ_{13} - operational hypothesis

W_{yg} Φ_5 Cross wind velocity - operational factor

independent / dependent - link between factors in Γ

➔ Usually, a single operational /design factor is not critically dangerous. More important and much more difficult to learn the effects of multi-factor combinations on flight safety. These multi-factor combinations are called operational/ design hypotheses.

Plan & Statistics of M&S Experiments For Selected Hypotheses

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Basic flight scenario		Operational hypothesis		Situational tree				
S_i	Name	Γ_k	'Formula'	$S_i \cdot \Gamma_k$	n	$i_1, \ldots, i_n$	Δt, s	$\Im \vert S_i \cdot \Gamma_k$, hrs
S_2	Normal takeoff, cross-wind	Γ_2	$W_{yg} \times \mu$	$S_2 \cdot \Gamma_2$	63	201, ..., 263	60	1.05
S_4	Normal takeoff, wind-shear	Γ_6	$k_W \times H_{FL}$	$S_4 \cdot \Gamma_6$	78	601, ..., 678	100	2.17
S_4	Normal takeoff, wind-shear	Γ_7	$\bar{x}_{CG} \times k_W \times (\theta_{G1} + \theta_{G2})$ $(\bar{x}_{CG} = \bar{x}_{CGmin})$	$S_4 \cdot \Gamma_7$	78	701, ..., 778	100	2.17
S_5	Continued takeoff, left-hand engine out during ground-roll, cross-wind	Γ_{10}	$\xi_{LHE} \times V_{EF} \times W_{yg}$	$S_5 \cdot \Gamma_{10}$	104	1001, ..., 1104	120	3.47
S_4	Normal takeoff, wind-shear	Γ_{12}	$k_W \times \theta_{G1} \times \gamma_G$ $(k_W = 1)$	$S_4 \cdot \Gamma_{12}$	130	1201, ..., 1330	60	2.17
S_6	Low-alittude climb, level flight or descent	Γ_{14}	$\theta_{G2} \times \gamma_G$	$S_6 \cdot \Gamma_{14}$	247	4001, ..., 4247	15	1.03

Legend: i – basic flight scenario code, S_i, $i \in \{1, \ldots, 6\}$; k – operational hypothesis (flight series) code Γ_k, $k \in \{1, \ldots, 14\}$; n – total number of 'flights' F_j in series $\Omega_k(F)$, $n = i_n - i_1 + 1$, $k \in \{1, \ldots, 14\}$, j – 'flight' code, $j \in \{i_1, \ldots, i_n\}$; Δt – planned duration of a 'flight' situation from $\Omega_k(F)$; $\Im \vert S_i \cdot \Gamma_k$ – virtual flight 'experience' accumulated in the situational tree (composition) $S_i \cdot \Gamma_k$.

➔ A composition of a basic scenario $\mathbf{S}_i$ and an operational hypothesis $\mathbf{\Gamma}_k$ in a M&S experiment generates a family of derivative ('neighboring') situations – a Situational Tree $\mathbf{S}_i \cdot \mathbf{\Gamma}_k$. Construction of a 'forest' of such trees – based on FMEA, flight test, operation or incident/ accident data – and studying their safety 'topology' are the overall goal of virtual flight test & evaluation/ certification. Situational trees are thought as a valuable artificial substitute for missing statistics on multi-factor flight accident/incident patterns.

$S_2 \cdot \Gamma_2$: Normal Takeoff. Variations Of Cross-Wind Velocity and ‘Wheels - Runway Surface’ Adhesion Factor

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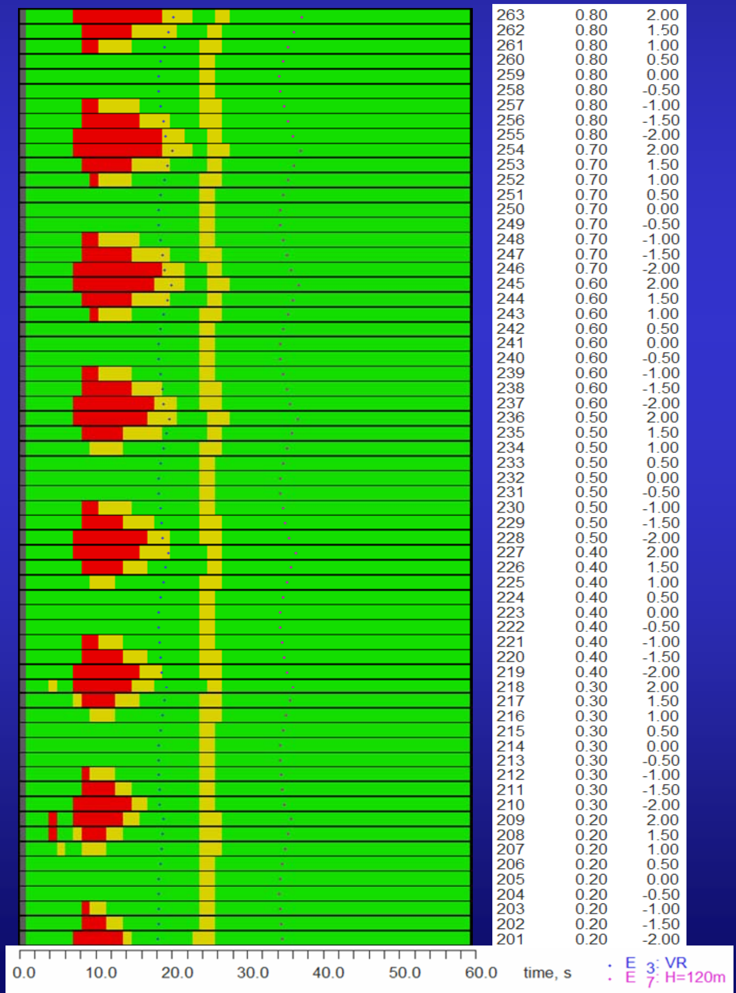
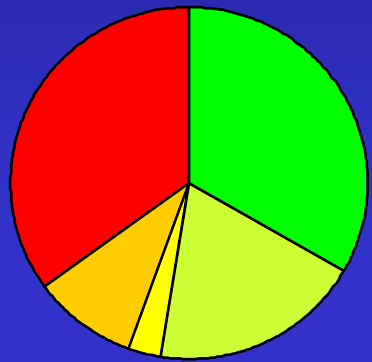
Integral Safety Spectra



i	μ	$k \cdot W_y$
263	0.80	2.00
262	0.80	1.50
261	0.80	1.00
260	0.80	0.50
259	0.80	0.00
258	0.80	-0.50
257	0.80	-1.00
256	0.80	-1.50
255	0.80	-2.00
254	0.70	2.00
253	0.70	1.50
252	0.70	1.00
251	0.70	0.50
250	0.70	0.00
249	0.70	-0.50
248	0.70	-1.00
247	0.70	-1.50
246	0.70	-2.00
245	0.60	2.00
244	0.60	1.50
243	0.60	1.00
242	0.60	0.50
241	0.60	0.00
240	0.60	-0.50
239	0.60	-1.00
238	0.60	-1.50
237	0.60	-2.00
236	0.50	2.00
235	0.50	1.50
234	0.50	1.00
233	0.50	0.50
232	0.50	0.00
231	0.50	-0.50
230	0.50	-1.00
229	0.50	-1.50
228	0.50	-2.00
227	0.40	2.00
226	0.40	1.50
225	0.40	1.00
224	0.40	0.50
223	0.40	0.00
222	0.40	-0.50
221	0.40	-1.00
220	0.40	-1.50
219	0.40	-2.00
218	0.30	2.00
217	0.30	1.50
216	0.30	1.00
215	0.30	0.50
214	0.30	0.00
213	0.30	-0.50
212	0.30	-1.00
211	0.30	-1.50
210	0.30	-2.00
209	0.20	2.00
208	0.20	1.50
207	0.20	1.00
206	0.20	0.50
205	0.20	0.00
204	0.20	-0.50
203	0.20	-1.00
202	0.20	-1.50
201	0.20	-2.00

Safety Chances Distribution



Category	ξ^j	n^j	χ^j, %
I	(green)	21	33
II-a	(yellow-green)	12	19
II-b	(yellow)	2	3
III	(orange)	6	10
IV	(red)	22	35
V	(black)	0	0
Σn^j, $\Sigma \chi^j$ | $S_2 \cdot \Gamma_2$:		63	100

Legend: i – ‘flight’ code, $k = 10^{-1}$, n^j – number of ‘flights’ belonging to safety cluster $\mathbf{K}^j$, χ^j – safety chances at ξ^j level, $\xi^j \in \{\xi^I, \dots, \xi^V\}$

➔ Scenario variants with strong cross-wind (|15| … |20| m/s) exhibit danger (enter ‘red’ zones) during groundroll, up to the event $\mathbf{E}_3$ (V_R) - ref. next slide for a safety window. Dangerous variants constitute some 45% of the situation domain belonging to the composition $\mathbf{S}_2 \cdot \mathbf{\Gamma}_2$. Remaining situations (55%) are safe. They belong to Categories **I** and **II**. Note how the location of events $\mathbf{E}_3$ and $\mathbf{E}_7$ in the integral safety spectra is changed due to the effect of (μ, W_{yg}) combinations.

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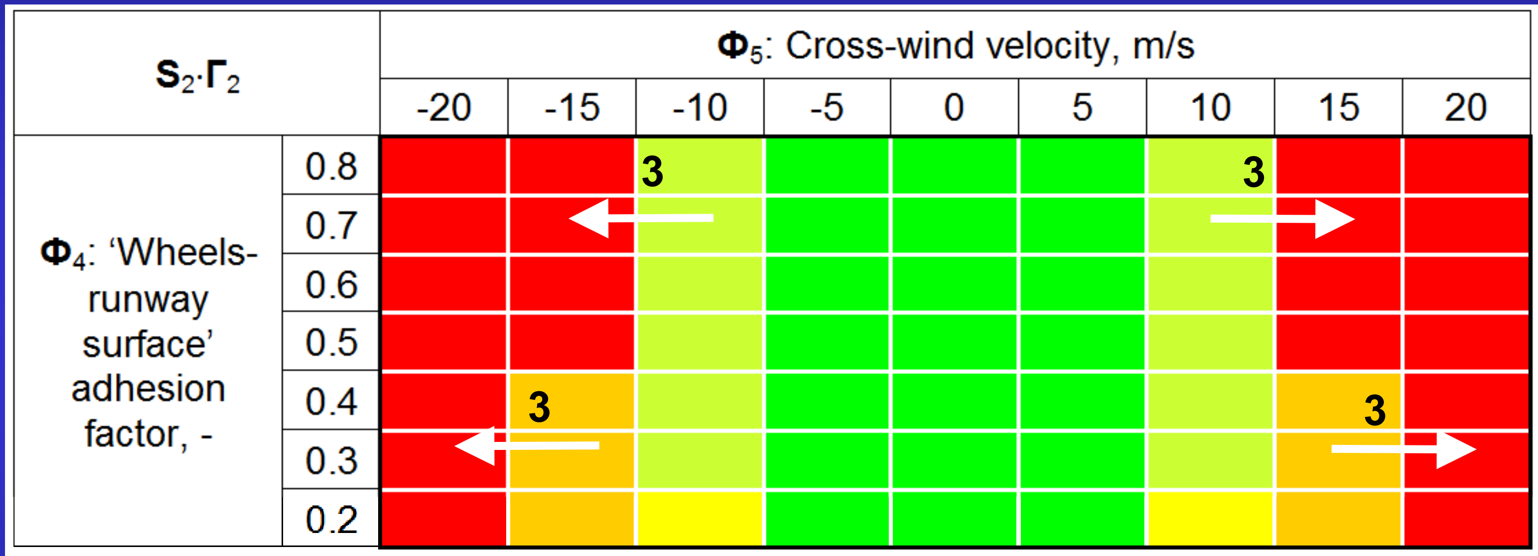
$S_2 \cdot \Gamma_2$: Normal Takeoff. Variations Of Cross-Wind Velocity and 'Wheels - Runway Surface' Adhesion Factor

Safety Window



➔ Shown above is a Safety Window constructed for the situational tree $\mathbf{S_2 \cdot \Gamma_2}$. It contains one central green 'valley', two side red 'hills' and two connecting 'slopes': a steep 'slope' – for semi-wet and dry runway (μ = 0.5. … 0.8), and not steep 'slope' - for wet and water-covered runway (μ = 0.2. … 0.4). As the absolute value of cross-wind velocity increases, the transition from a safe state to a dangerous state occurs sharply and gradually, respectively. The shape and position of the 'cross-wind velocity – adhesion factor' constraint can be seen as well.

$S_4 \cdot \Gamma_6$: Normal Takeoff. Variations Of Wind Shear Intensity and Errors of Selection of Flap-up Start Altitude

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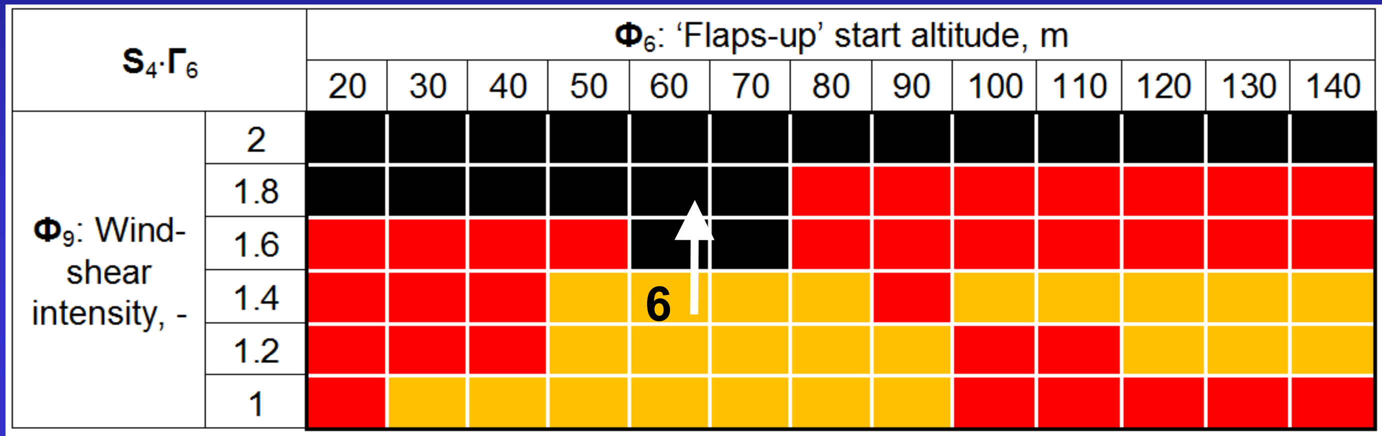

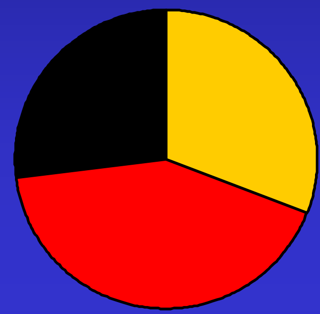

➔ (Note: in the baseline scenario S_4 θ_{G1}/θ_{G2} = 8º/8º). If a 'strong' or worse wind shear is expected ($k_W \geq 1$), takeoff must be prohibited. In order to evaluate the possibility of safer outcomes at $k_W < 1$, it is expedient to expand the safety window downward. If the wind shear intensity increases from 'very strong' ($k_W > 1.4$) to 'hurricane' ($k_W = 2$), 'precipice' type transitions (**6**) are most likely to occur at flap-up start altitude $H_{FL} \in [60; 70]$ м. If the vehicle unintentionally enters a zone of 'very strong' wind- shear (k_W = 1.2 …1.6) high-lift devices must be retracted as late as possible to keep the vehicle within the right-hand 'orange' zone.

Category	ξ^j	n^j	χ^j, %
I		0	0
II-a		0	0
II-b		0	0
III		24	31
IV		33	42
V		21	27
Σn^j, $\Sigma \chi^j$ | $S_4 \cdot \Gamma_6$:		78	100

$S_4 \cdot \Gamma_7$: Normal Takeoff. Forward C.G. Variations of Wind Shear Intensity And Commanded Flight Path Angles

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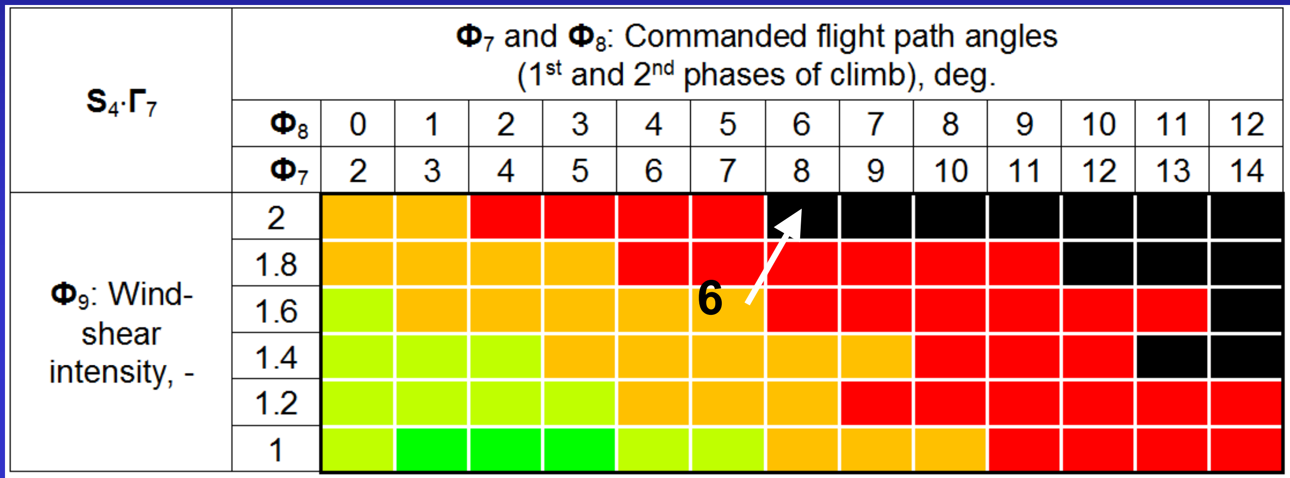

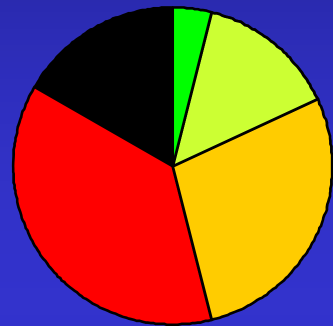

➔ The main safety topology objects of the composition $S_4 \cdot \Gamma_7$ are: a small green ‘valley’ located at the left-hand lower corner, an orange ‘slope’, and an extensive red ‘hill’ adjacent to a black ‘abyss’ at the right-hand upper corner. At takeoff under ‘strong’ and ‘very strong’ wind shear conditions ($1 < k_W \leq 1.6$), a maximum possible safety level is achieved at $\theta_{G1}/\ \theta_{G2} = 5^o/3^o$. Therefore, attempts of climbing at $\theta_{G1}/\ \theta_{G2} > 7^o/5^o$ must be prohibited, and a zone of irreversible transitions is likely to enlarge significantly at $\theta_{G1} \geq 12^o$.

Category	ξ^j	n^j	χ^j, %
I		3	4
II-a		11	14
II-b		0	0
III		22	28
IV		29	37
V		13	17
Σn^j, $\Sigma \chi^j$ | $S_4 \cdot \Gamma_7$:		78	100

$S_5 \cdot \Gamma_{10}$: Continued Takeoff. Engine Out at V_{EF}. Variations of Engine Out Speed and Cross-Wind Velocity

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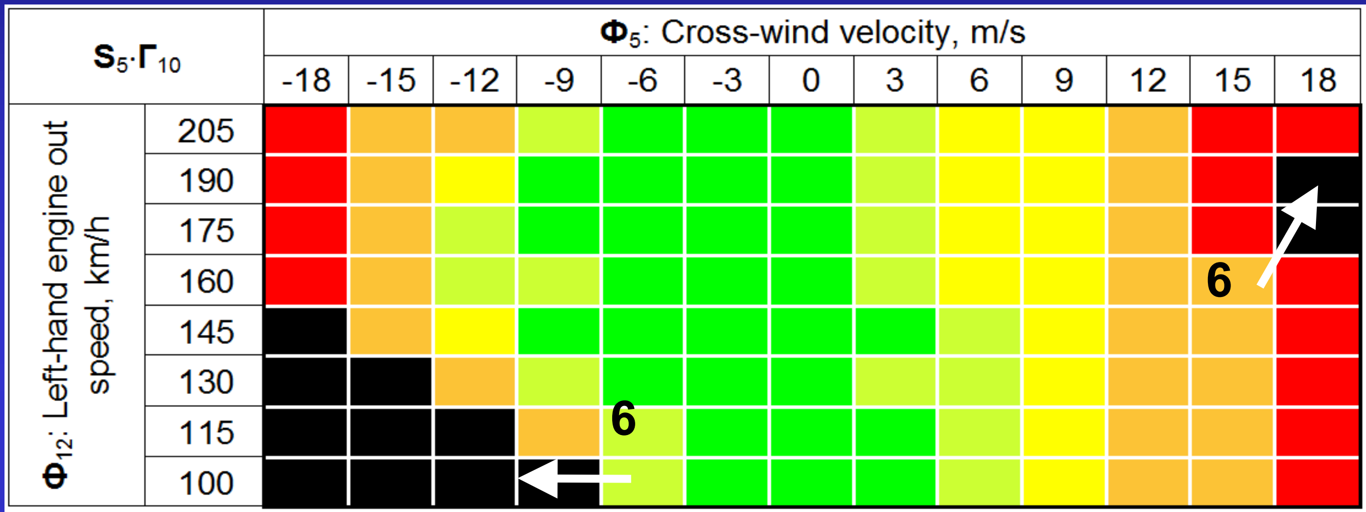
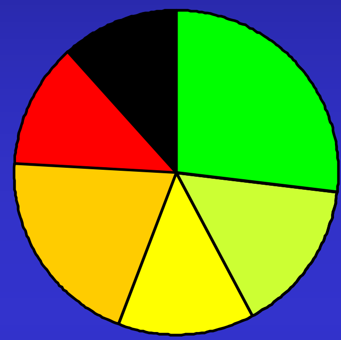
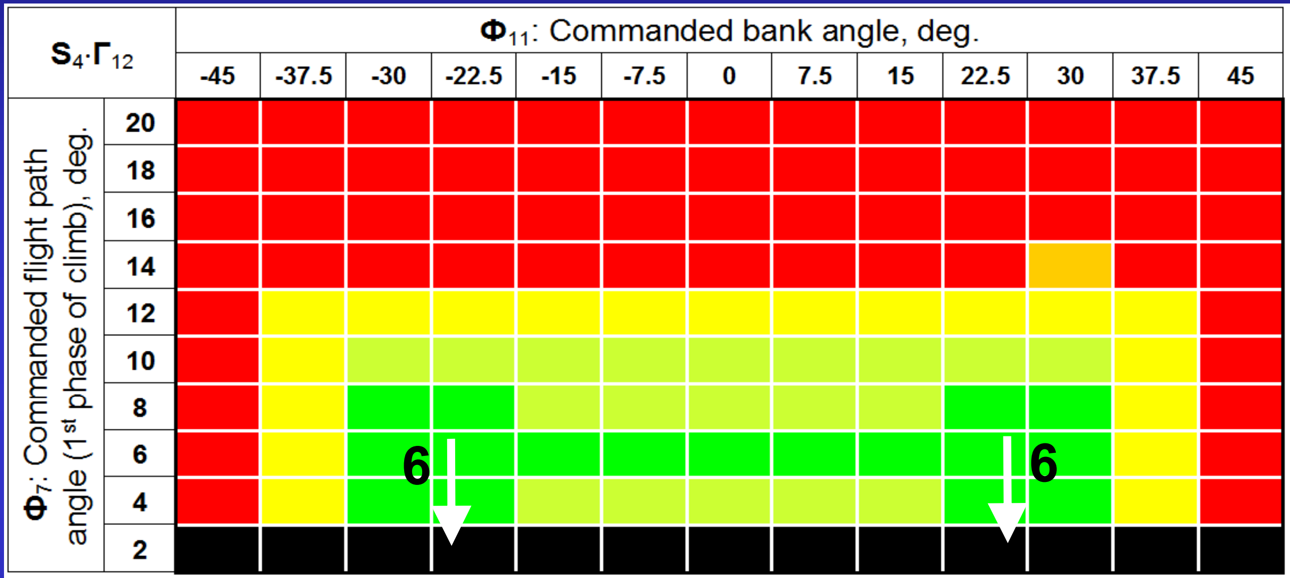


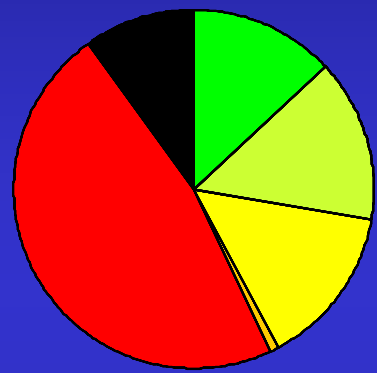


➔ This safety window contains one central green 'valley' and two side red 'hills'. Adjacent to the left-hand 'hill' is a potentially catastrophic 'abyss' located at the lower left-hand corner. It corresponds to small and medium values of V_{EF} and is linked to the 'valley' by 'precipice' type transitions (**6**). A small 'abyss' is also revealed at a cross-wind velocity of ~18 m/s and engine-out speed of $V_{EF} \in [175; 190]$ km/h.

Category	ξ^j	n^j	χ^j, %
I		28	27
II-a		16	15
II-b		14	13
III		21	20
IV		13	13
V		12	12
Σn^j, $\Sigma \chi^j$ | $S_5 \cdot \Gamma_{10}$		104	100

$S_4 \cdot \Gamma_{12}$: Takeoff. ‘Strong’ Wind Shear. Errors of Selecting Commanded Flight Path and Bank Angles in Climb





➔ Safety ‘topology’ obtained for ‘strong’ wind shear conditions at small flight path angles θ_{G1} and any bank angles γ_G contains a stable catastrophic ‘abyss’ (a black strip at the bottom of the window) and “precipice’ type transitions (**6**). It means that attempts of climb at small values of the commanded flight path angle (1º … 2º) would inevitably lead the vehicle to a fatal outcome.

Category	ξ^j	n^j	χ^j, %
I		17	13
II-a		19	15
II-b		19	15
III		1	1
IV		61	46
V		13	10
Σn^j, $\Sigma \chi^j$ | $S_4 \cdot \Gamma_{12}$		130	100

Situational Trees and Short-Term Prediction of Flight Safety

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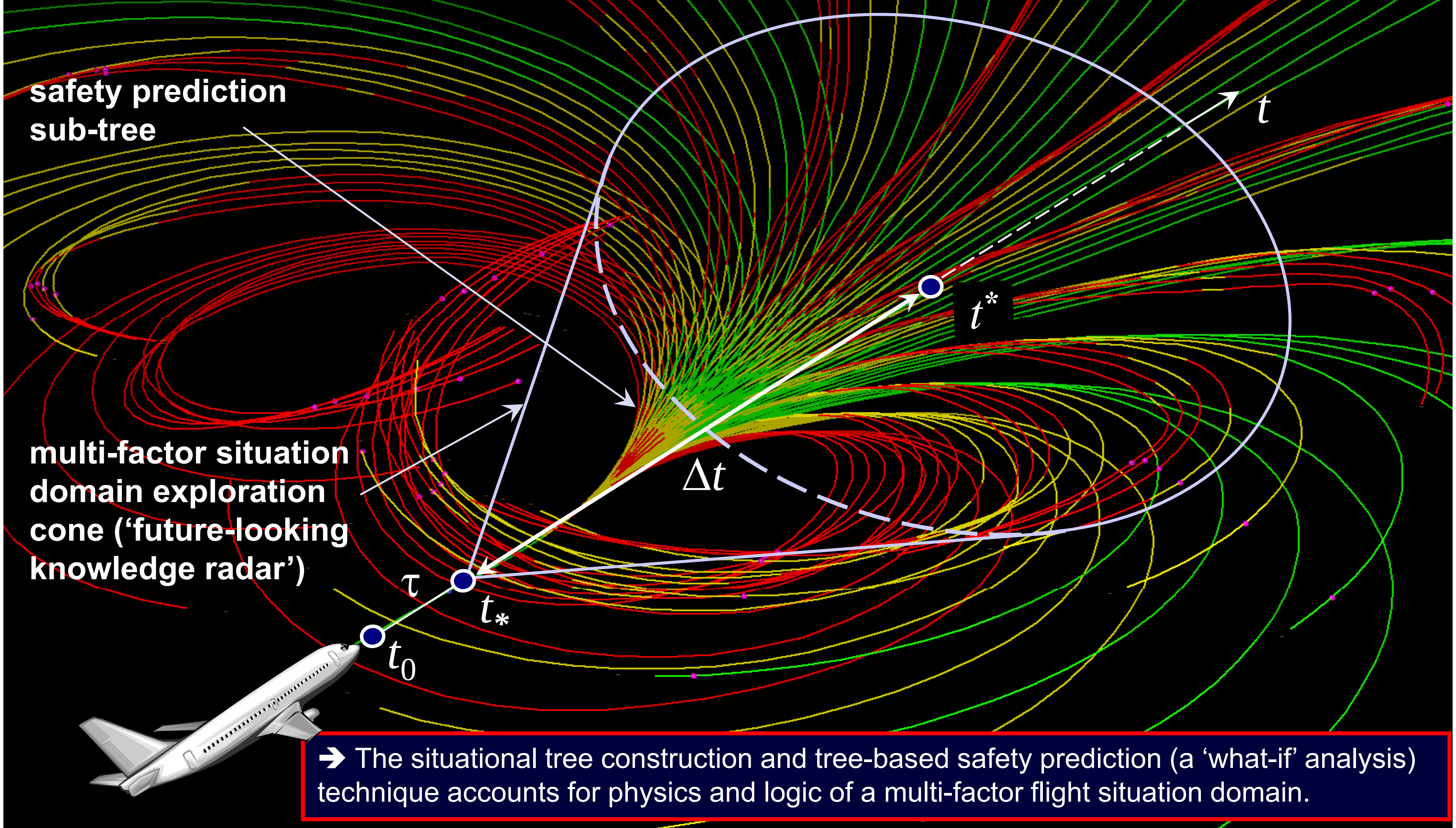
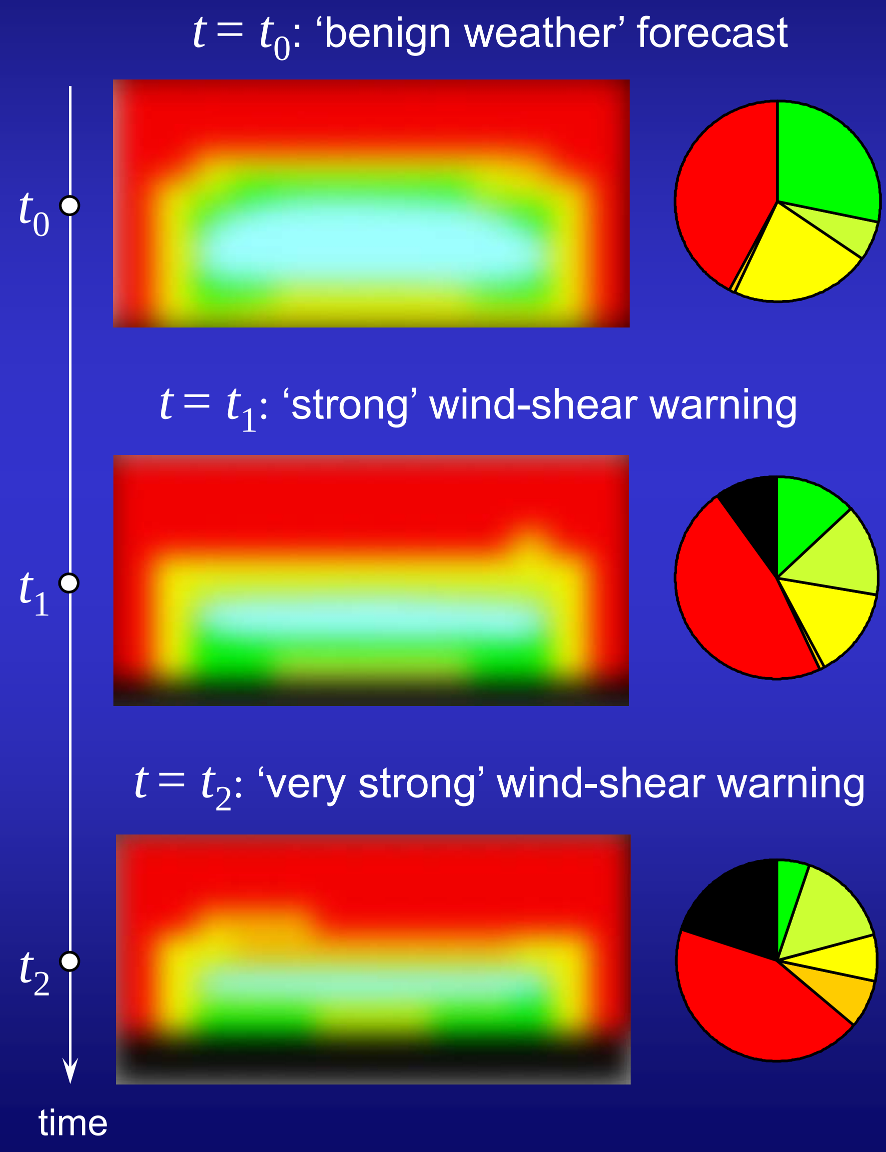
Legend: t_o – current flight time, t_* – prediction start time, t^* – prediction stop time, $\tau = (t_* - t_o)$ – decision-making delay, $\Delta t = (t^* - t_*)$ – prediction time range (depth of tree-based multi-factor domain exploration)



➔ The situational tree construction and tree-based safety prediction (a 'what-if' analysis) technique accounts for physics and logic of a multi-factor flight situation domain.

Real-Time Safety Knowledge Map (Dynamic Safety Window) Example



A time-history of safety windows and safety chances distribution pie charts is shown. It corresponds to a notional complex flight situation domain - a union of three compositions $\mathbf{S}_4 \cdot (\mathbf{\Gamma}_{11}+\mathbf{\Gamma}_{12}+\mathbf{\Gamma}_{13})$: "Normal takeoff. Possible variations of wind-shear intensity, errors/ variations in maintaining commanded flight path and bank angles during initial climb".

➔The concept of Dynamic Dafety Window is based on the use of a 'forest' of situational trees. Provided that key operational factors are measurable on board the vehicle in real time, the dynamic safety window can be used as a medium for coherent monitoring of tactical goals and constraints of flight under uncertainty. Safety Chances Distribution pie charts are expedient to use in onboard safety indicators to monitor current states and predict the dynamics of the system safety chances under anticipated operational conditions during flight.

➔ Note that in this particular example, the share of 'red' and 'black' scenario options increases at the expense of reducing the share of safer outcomes.

$S_6 \cdot \Gamma_{14}$: Low-Altitude Flight in the Presence of Urban Obstacles ('9/11')

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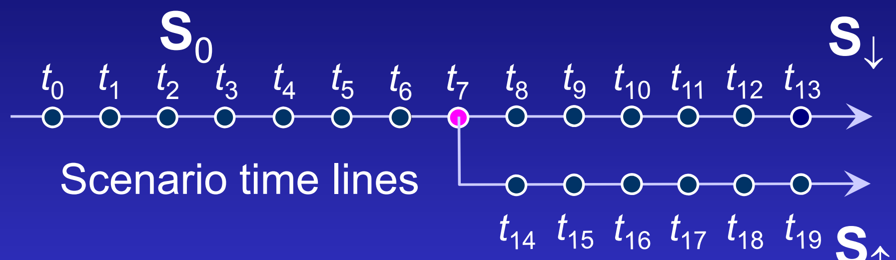
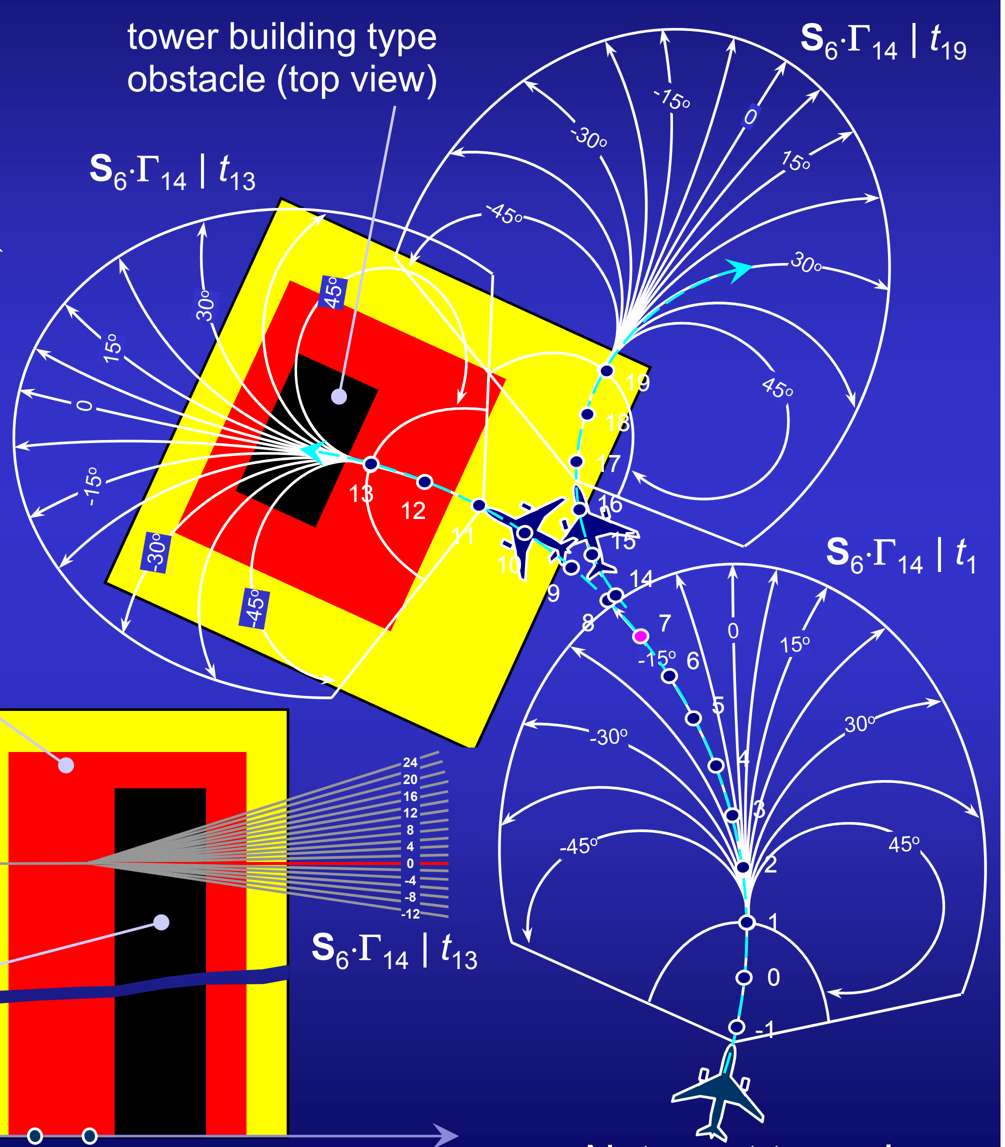
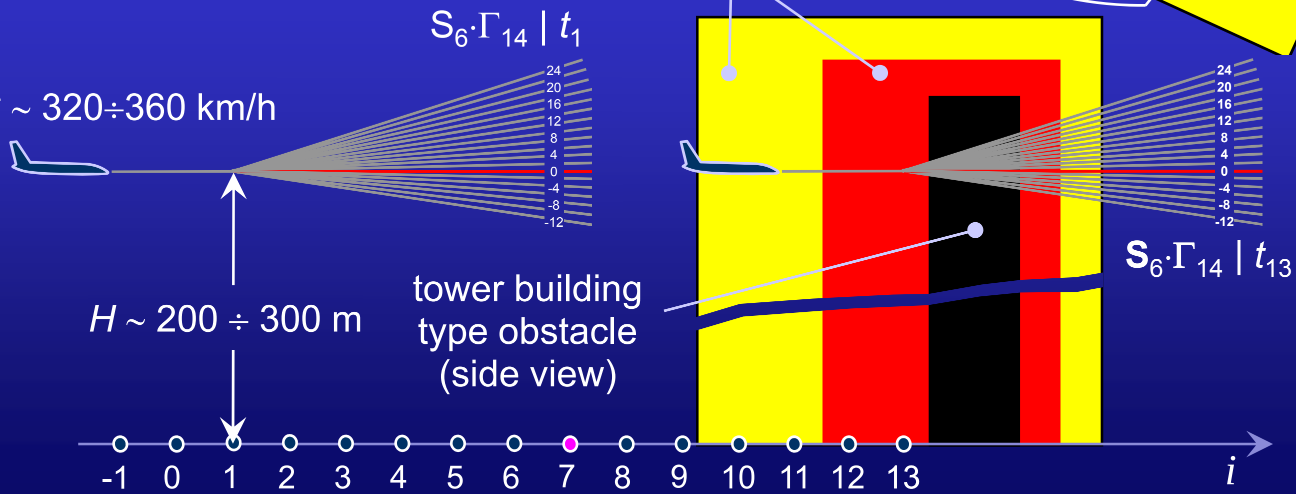


Legend:
S_0, **$S_\downarrow$**, **$S_\uparrow$** - scenario segments, **S_0** - obstacle approach, **$S_\downarrow$** - imminent collision, **$S_\uparrow$** - collision avoidance, **$S_6 \cdot \Gamma_{14} \mid t_i$** - tree projection at t_i

➔ **$S_0 \cup S_\downarrow$** - terrorist-/ fool-type control, **$S_0 \cup S_\uparrow$** - AI-based self-preservation control.

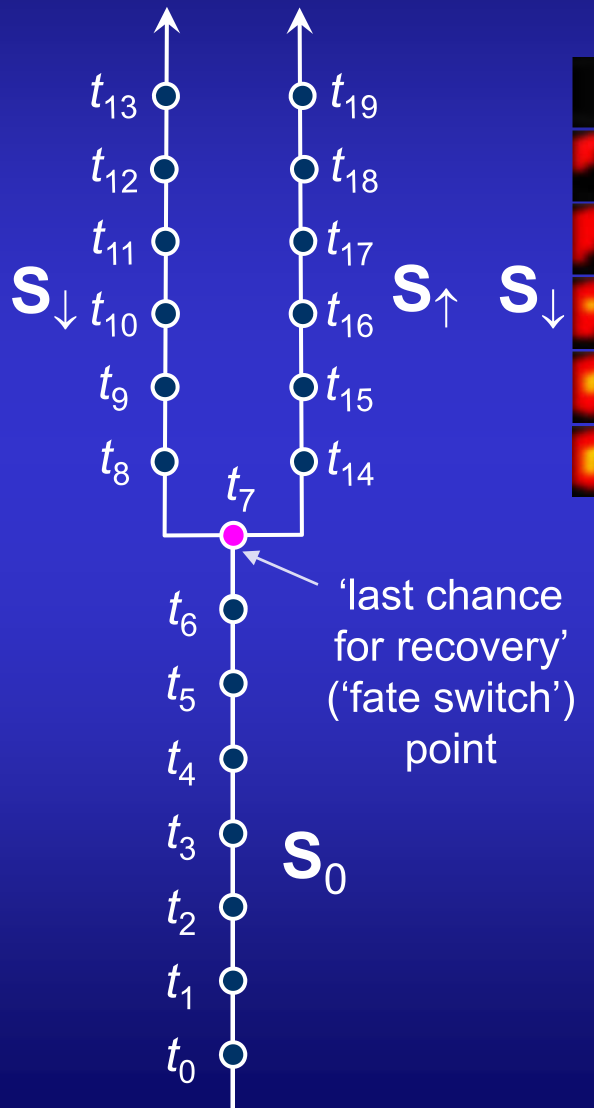
'yellow' and 'red' zones of the obstacle's fuzzy constraint

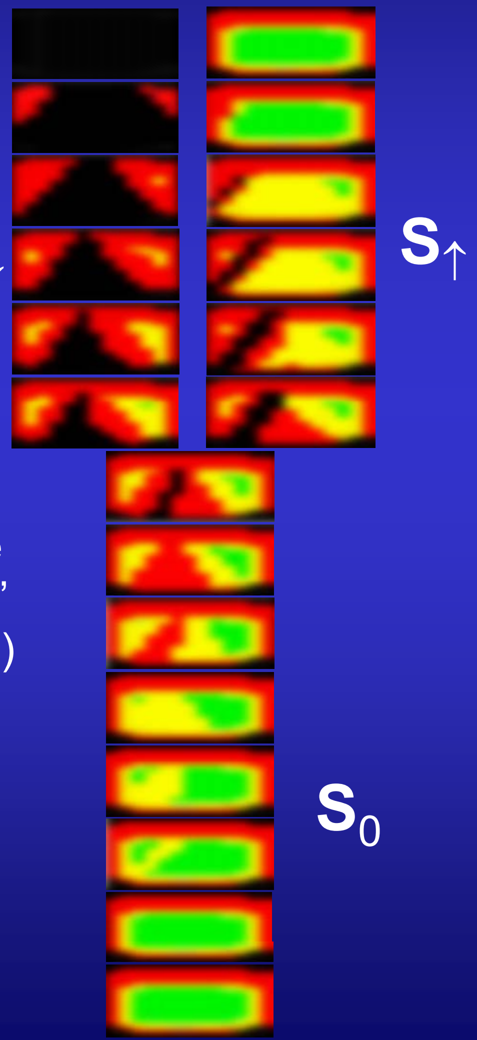




Note: not to scale

‘Bird’s Eye’ View of the Dynamic Safety Window Tree for Catastrophic and Recovery Scenarios





➔ This safety window time-history provides a systematic – ‘bird’s eye’ view level – picture of two alternative scenarios of aircraft flight control in the presence of an urban type obstacle, as a part of a multi-factor flight situation domain-‘neighborhood’.

Legend:

Scenario segments:

- $\mathbf{S}_0$ – obstacle approach
- $\mathbf{S}_\downarrow$ – imminent collision
- $\mathbf{S}_\uparrow$ – AI based collision avoidance

Scenario development time lines:

- $\{t_0, t_1, \ldots, t_7\}$ – $\mathbf{S}_0$
- $\{t_8, \ldots, t_{13}\}$ – $\mathbf{S}_\downarrow$
- $\{t_{14}, \ldots, t_{19}\}$ – $\mathbf{S}_\uparrow$

Key time instants:

- t_7 – ‘last chance for recovery’
- t_{13} – ‘just before impact’
- t_{19} – ‘safety restoration complete’

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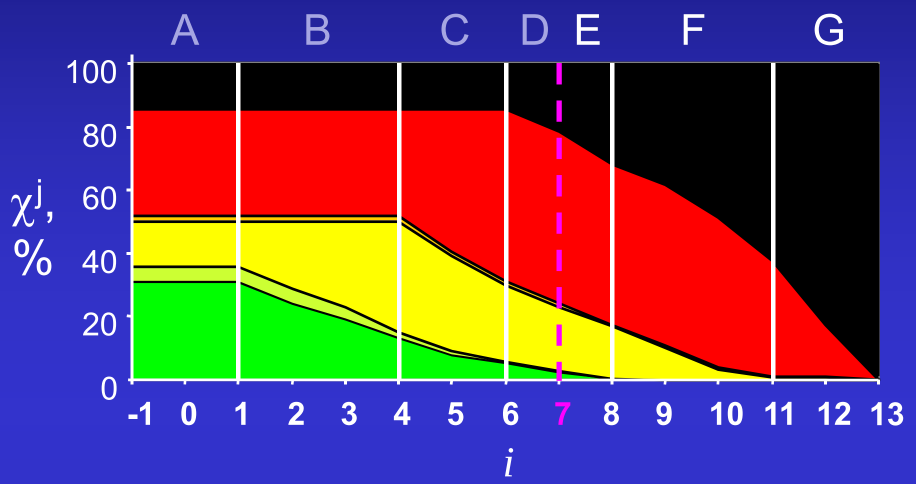
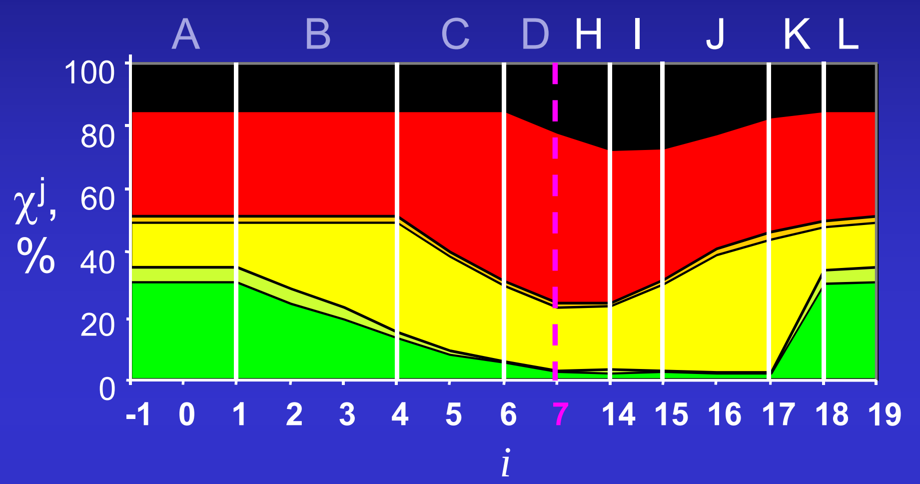
Safety Chances Distribution Time-History for Two Control Tactics

terrorist-/ fool-type control tactics



AI based self-preservation control tactics



Legend: A, B, …, L – characteristic states of the aircraft safety dynamics; χ^j – safety chances at ξ^j level, $j \in$ {**I**, **II-a**, **II-b**, **III**, **IV**, **V**}; t_i – flight time instants, $i \in \{-1, 0, 1, \ldots, 13\} \vee i \in \{-1, 0, 1, \ldots, 7, 14, 15, .., 19\}$.

I | **II-a** | **II-b** | **III** | **IV** | **V** – Safety Classification Categories and Safety Colors.

➔ Characteristic states {A, B, C, …, L} of the vehicle's safety dynamics and their recognition criteria are expedient to use in the automatic or manual recovery decision-making process in emergency situations under uncertainty. In accordance with the self-preservation imperative for a civil aircraft, flight control authority in a life-threatening situation must be dynamically assigned/transferred to a most competent agent.

A detailed presentation of this case study, titled ***UAV "Built-in" Safety Protection: A Knowledge-Centered Approach***, which introduces the Dynamic Safety Window, Safety Chances Distribution and some other concepts indended for real-time applications, is planned (tentatively) to make at the AUVSI's Unmanned Systems Europe 2007 Conference, 8-9 May 2007, Hilton Cologne, Köln, Germany.

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Conclusion

1. The presented methodology is **an affordable M&S tool** for an aircraft/ project **'virtual flight testing' in multi-factor situations**. It is specially designed for **quick, 'bird's eye view' level analysis** of the vehicle's safety performance **under uncertainty** based on M&S data.

2. The goal is to help **identify in advance anomalous** scenarios ('theoretically improbable' cases) in the 'operator (pilot, automaton) – aircraft – operational environment' system behavior, **taking into account physics and logic of a 'what-if' flight situation domain**.

3. The methodology is expedient to integrate into **MDO systems, FMEA tools, flight test planning/ 'rehearsal'** and output data analysis processes, and test pilot theoretical training.

4. However, **a reliable 'parametric definition'** of the vehicle under study **is a pre-requisite** for obtaining valid results from the system model. It must encapsulate a subdomain of the vehicle motion, control and operational modes of interest.

5. Potential application fields include the following:

- advanced assessment of **combined effects** of the vehicle aerodynamics, flight control and operational conditions on its safety performance
- **rehearsal of flight test cases** under difficult-to-manage multi-factor conditions in M&S
- **knowledge-centered training** of test pilots, pilot instructors, and line pilots
- research into terrorist-/ fool-proof **AI systems for aircraft safety** protection
- research into **UAV autonomous control and collision avoidance** under uncertainty.

6. The overall goal is to help **design and test aircraft with 'built-in' safety** features based on virtual (not actual) statistics of 'incidents'/ 'accidents' derived from branching M&S experiments.

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France

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Thank You.

Questions, please …

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Selected Publications

1. Burdun, I.Y., "Prediction of Aircraft Safety Performance in Complex Flight Situations" (Paper 2003-01-2988), *Proc. of the 2003 Advances in Aviation Safety Conference, September 8-12,* 2003, *Montreal*, *Canada,* SAE, 2003, 18 pp.

2. Burdun, I.Y., "Studying Physics and Logics of Complex Flight Situation Domains by Means of VATES Modeling and Simulation Tool", *2nd Science and Technology Conference "Flight Simulation Technologies and Pilot Training: New Approaches and Goals", TsAGI, 24-25 April 2003, Zhoukovsky, Moscow Region,* Russia, 2003, 11 pp. (in Russian).

3. Burdun, I.Y., Parfentyev, O.M., "Fuzzy Situational Tree-Networks for Intelligent Flight Support", *Int. Journal of Engineering Applications of Artificial Intelligence (EAAI)*, 12 (1999), pp. 523-541.

4. Burdun, I.Y., "The Intelligent Situational Awareness And Forecasting Environment (The S.A.F.E. Concept): A Case Study" (Paper 981223), *Proc. of 1998 Advances in Flight Safety Conference and Exhibition, April 6-8, 1998, Daytona Beach, FL, USA* (P-321), SAE, 1998, pp. 131-144.

5. Burdun, I.Y., and Mavris, D.N, "A Technique for Testing and Evaluation of Aircraft Flight Performance In Early Design Phases" (Paper 975541), *Proc. of the World Aviation Congress (WAC'97), Anaheim, Oct. 1997, CA,* AIAA-SAE, 1997, 13 pp.

6. Burdun, I.Y., and Burdun, E.I., 'VATES – Virtual Autonomous Test and Evaluation Simulator' (Version 7 – Professional), User's Manual, 2000, 155 pp.

