REDUCING EXPOSURE TIME IN PONTOON BRIDGE EMPLACEMENT UNDER PERSISTENT DRONE ISR: ENGINEERING SOLUTIONS FOR RAPID ASSEMBLY AND SHORE CONCEALMENT

Gordana Simić

University of Niš
Niš, Republic of Serbia
E-mail: gordana.simic@masfak.ni.ac.rs

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Abstract: Wet-gap crossing has become one of the most dangerous engineering tasks on the contemporary battlefield, because a pontoon bridge is a large, fixed, thermally and geometrically conspicuous structure that must remain in place long enough for a force to cross, all under persistent unmanned reconnaissance. This article asks a narrow question: what determines whether a crossing survives, and where should engineering effort be spent to reduce the exposure that gets bridging units killed? The study reframes survivability as a race between two clocks. The first is the total exposure time of the crossing site — the sum of assembly, trafficking, and recovery; the second is the adversary's reconnaissance-strike loop, the interval from first detection to delivered effect. Its original contribution is the Crossing Exposure Index (CEI), defined as the ratio of total exposure time to the reconnaissance-strike loop time, together with a concealment-adjusted survivability function in which probability of completing the crossing before a strike arrives decays exponentially with the exposure that overhangs the enemy loop, scaled by a concealment-reduced detection rate. The model yields a sharp design rule absent from the bridging and operations-research literatures alike: when exposure is driven below the loop time, the crossing completes inside the adversary's decision cycle and timely engagement becomes near-impossible, whereas above that threshold survivability falls off rapidly and concealment, not further speed, governs the residual. Illustrative computation across assembly times of 30 to 150 minutes, loop times of 10 to 40 minutes, and concealment effectiveness of zero to eighty percent produces modelled crossing-survival probabilities ranging from below 0.10 for a slow, unconcealed crossing against a fast loop to above 0.90 for a rapid, well-concealed crossing. The analysis concludes that exposure reduction is a systems problem: modular and parallel assembly to compress the timeline, signature management to lower the detection rate, and sequencing to keep the detectable window beneath the enemy loop, each insufficient alone. All numerical values are model-derived and require empirical and exercise validation before use.

Keywords: *wet-gap crossing, pontoon bridge, exposure time, drone ISR, reconnaissance-strike loop, camouflage and concealment, military survivability.*

INTRODUCTION

A river is the cheapest defensive line an army can be handed, and crossing one under fire has always been costly. What has changed is that the cost is now imposed not by the defender on the far bank alone but by a camera in the sky — one that never blinks. Persistent unmanned intelligence, surveillance, and reconnaissance has made the rear-area engineering site as visible as the forward trench, and the wet-gap crossing, by its nature a fixed, large, and slow undertaking, is among the most exposed activities a modern force performs. Battlefield analysis of the Russia-Ukraine war documents how cheap one-way attack drones, fielded in mass, convert any detected concentration into a target within minutes (Plichta, 2025), and how the resulting transparency of the front has pushed both sides toward attrition dynamics in which survivability hinges on not being seen, or not being seen long enough to be struck (Gady & Kofman, 2024).

The pontoon bridge concentrates every vulnerability at once. It is geometrically linear and therefore easy to recognise from oblique aerial imagery; it generates thermal and wake signatures on the water; it requires vehicles, cranes, and boats to mass at two shorelines; and, once built, it cannot move. Engineering literature has made floating and modular bridges structurally excellent, with well-characterised dynamic response to wave, current, and moving loads (Miao et al., 2021; Zhang & Li, 2021; Fenerci et al., 2022), but structural excellence does not address the survivability problem, which is fundamentally one of time and visibility rather than of stress and deflection. A bridge that performs perfectly for two hours is of little use if the crossing is destroyed in the first thirty minutes.

The doctrinal and operations-research treatment of wet-gap crossing has, for its part, concentrated on site selection and hydrographic suitability, for instance the optimisation of water-depth values for crossing means (Sedláček & Dohnal, 2021) and the development of geoprocessing tools to identify feasible crossing sites (Sedláček & Dohnal, 2024). Parallel work has quantified the effectiveness of aerial reconnaissance against ground forces through constructive simulation, showing that even modest unmanned reconnaissance sharply raises the probability that a force-protection task is compromised (Drozd et al., 2021), and has built survivability metrics for unmanned-vehicle tactics (Lunsford & Bradley, 2021). What none of this work does is join the two sides of the ledger, the engineering time to build and clear a crossing on the one hand, and the adversary's sensor-to-shooter timeline on the other, into a single quantity that tells an engineer how fast is fast enough.

The central research question follows from that gap. For a pontoon crossing under persistent drone ISR, what is the relationship between the total exposure time of the site and the adversary's reconnaissance-strike loop, and where, given that relationship, should engineering effort be concentrated to maximise the probability that the crossing completes before a strike arrives? Three hypotheses structure the inquiry. The first holds that the binding constraint on survivability is the ratio of total exposure time to the reconnaissance-strike loop time, not assembly time considered in isolation, and that driving exposure below the loop time confers near-immunity to timely engagement. The second holds that assembly-time reduction through modularity and parallel emplacement yields diminishing survivability returns once exposure exceeds the loop time, unless it is paired with concealment that lowers the rate at which the site is detected. The third holds that shore concealment functions as a detection-rate multiplier that extends effective survivability rather than as absolute invisibility, and that its marginal value rises steeply as exposure approaches the loop time.

The original contribution of this article is the Crossing Exposure Index (CEI) and its associated survivability function. The index is the ratio of total exposure time to the reconnaissance-strike loop time; the survivability function expresses the probability of completing the crossing before a strike as an exponential decay in the exposure that overhangs the loop, scaled by a detection rate that concealment reduces. To my knowledge no prior study couples bridging-engineering timelines, concealment-modulated detectability, and the drone reconnaissance-strike cycle into one expression, and it is that coupling, rather than any single term, that produces the design rule the article defends:

reduce exposure beneath the loop time first, then attack the residual detectability with concealment. The bridging literature optimises structures and assembly in isolation, the camouflage literature optimises signature in isolation, and the operations-research literature optimises sites and reconnaissance effectiveness in isolation; the CEI is the instrument that makes their interaction legible to a planner.

The remainder of the article proceeds as follows. A review situates the problem across the floating-bridge, accelerated-construction, target-detection, camouflage, and military-operations-research literatures and isolates the gap the index fills. The methodology defines the CEI and its survivability function and states the model's inputs and limits. A results section reports illustrative index and survivability values across a realistic parameter space. Four analytical sections then interpret those results, treating in turn the primacy of the reconnaissance-strike loop, the engineering of the assembly timeline, concealment as a detection-rate multiplier, and the integration of these into a survivable crossing architecture. A conclusion returns to the three hypotheses.

LITERATURE REVIEW AND METHODOLOGY

Literature Review

The structural-engineering literature on floating and modular bridges is mature and supplies the assembly-and-trafficking side of the problem. The dynamic response of pontoon bridges to the combined action of waves, currents, and moving vehicle loads has been modelled and validated in detail (Miao et al., 2021), and hinged-girder configurations under moving loads are well characterised (Zhang & Li, 2021). The hydrodynamic interaction between adjacent pontoons, which governs how a multi-bay floating structure behaves dynamically, has been quantified for long bridges (Fenerci et al., 2022), and the shielding effect of nearby floating bodies on bridge response has been studied experimentally and numerically (Huang et al., 2023). Recent hydroelastic analysis extends this to plate-type very large floating structures under multi-lane moving vehicle loads (Jiang et al., 2026). For the present argument the relevance of this body of work is indirect but real: it establishes that the trafficking phase, the time a force spends actually crossing, is bounded below by dynamic and load-rating constraints that cannot be wished away, and therefore that exposure cannot be compressed without limit by speed alone.

The accelerated-construction and modular-bridging literature supplies the assembly-time side directly. Accelerated bridge construction as a discipline is built precisely around moving work off the critical on-site path through prefabrication and modular elements (Azizinamini, 2020), and cost-effective ultra-high-performance concrete has been developed specifically to enable such methods (Wang et al., 2021). Modular truss and double-truss systems have been investigated experimentally and analytically for stability and capacity (Embaby & El Naggar, 2025a; Embaby & El Naggar, 2025b) and for the behaviour of their steel shear panels (Embaby & El Naggar, 2024), while the classic Bailey bridge retains quantifiable load capacity in modern civil and military use (Prokop et al., 2022). The dynamic load allowance of long-span modular steel bridges has been characterised for traffic effects (Chordà-Monsonís et al., 2023), and a modular truss bridge has been dynamically load-tested using military vehicles, a direct point of contact with the wet-gap problem (Pinkney et al., 2022). Tellingly, production-scheduling research shows that modular assembly time is itself an optimisation target amenable to metaheuristics and parallel sequencing (Peiris et al., 2023), which is the engineering lever the present model exploits.

The threat side is documented across drone-warfare and military operations-research literature. The mass employment of one-way attack drones has been assessed as a campaign-level phenomenon that compresses the interval between detection and effect (Plichta, 2025), within a broader attritional logic in which battlefield transparency is decisive (Gady & Kofman, 2024). Constructive simulation has quantified how aerial reconnaissance degrades force protection (Drozd et al., 2021), survivability metrics have been formalised for unmanned-vehicle tactics (Lunsford & Bradley, 2021), and autonomous drone behaviours have been simulated in contested anti-access environments (Martinez et al., 2024). The counter-drone side, including standardised evaluation of counter-UAS performance, completes the picture of a contest measured in minutes (De Cubber et al., 2025). This literature establishes the reconnaissance-strike loop as a real, estimable interval, which is the quantity the present model places in the denominator of its index.

Detectability, the parameter that concealment acts upon, is illuminated by the rapidly advancing literature on target detection from unmanned platforms. Detection of military targets on ground and sea by UAVs at low-altitude oblique perspectives has been demonstrated (Zeng et al., 2024), real-time vehicle detection from aerial imagery is now routine with improved deep networks (Li et al., 2023), and the field has been surveyed comprehensively (Tang et al., 2023). Detection robust to poor visibility has advanced through visible-thermal fusion with transformer architectures (Chen et al., 2024), and, most pertinently, deep-learning detection of deliberately camouflaged military objects has been developed with purpose-built datasets (Hwang & Ma, 2024). The clear implication is that concealment now contends with automated, multi-spectral detection, and that its effect is best modelled as a reduction in detection rate rather than as a binary cloak.

The concealment literature itself supplies that side. Infrared camouflage textile materials have advanced to address thermal detection (Su et al., 2023), broadband UV-visible-infrared camouflage textiles target multidimensional surveillance backgrounds (Hossain, 2024), and infrared-screening smokes, including red-phosphorus compositions, degrade thermal and optical sensing of an area for a controllable interval (Dam Quang et al., 2022). Read together with the detection literature, these works define a measurable contest between sensing and hiding. The gap that remains, and that this article addresses, is the absence of any framework joining the engineering exposure timeline, the concealment-modulated detection rate, and the reconnaissance-strike loop into a single survivability quantity. The CEI is offered to fill it.

Research Methodology

The design is analytical and model-based rather than experimental, and I should be candid about why: I have neither a river nor an opposing reconnaissance complex to instrument, and inventing field timings would defeat the purpose. The method therefore synthesises published, peer-reviewed data into a transparent model whose inputs are traceable and whose outputs are labelled as model-derived pending validation. The model has three components. The first decomposes total exposure time into assembly, trafficking, and recovery, with ranges informed by the modular and accelerated-construction literature (Azizinamini, 2020; Pinkney et al., 2022; Peiris et al., 2023). The second represents the adversary reconnaissance-strike loop as an interval estimated from the drone-warfare literature (Plichta, 2025; Drozd et al., 2021). The third joins them through a detection process whose rate concealment reduces, drawing on the detection and camouflage literatures (Hwang & Ma, 2024; Su et al., 2023).

The Crossing Exposure Index is defined as CEI = T_exp / T_rs, where T_exp is the total exposure time of the crossing site, equal to the sum of assembly time T_a, trafficking time T_t, and recovery time T_r, and T_rs is the adversary reconnaissance-strike loop, the interval from first detection of the site to the arrival of a delivered effect. The survivability of the crossing is modelled by treating detection as a Poisson process of rate lambda over the exposure window. A site detected at time t is struck at t plus T_rs, so the crossing is lost only if it is detected earlier than a time T_rs before completion; that is, within an interval of length max(0, T_exp − T_rs). The probability of completing the crossing before a strike is therefore P_cross = exp(−lambda · max(0, T_exp − T_rs)), and the detection rate is written lambda = lambda_0 · (1 − C), where lambda_0 is the baseline detection rate against an unconcealed site under a given ISR density and C is concealment effectiveness on the unit interval. The structure of this expression carries the central result: when T_exp is less than or equal to T_rs, the overhang term is zero, P_cross equals one, and the crossing completes inside the adversary's loop irrespective of detection. Only when CEI exceeds one does survivability begin to decay, and it then decays exponentially in the product of the overhang and the concealment-reduced detection rate.

The parameter space is bounded by what wet-gap operations plausibly present. Total exposure time is examined over 30 to 150 minutes, bracketing a rapid single-purpose ribbon crossing at the low end and a deliberate multi-span operation with heavy traffic at the high end, with assembly itself informed by the order-of-magnitude reductions that modular and accelerated methods deliver (Azizinamini, 2020; Peiris et al., 2023). The reconnaissance-strike loop is examined over 10 to 40 minutes, spanning a contested environment with a tight sensor-to-shooter cycle and a more permissive or degraded one (Plichta, 2025; Drozd et al., 2021). Concealment effectiveness is examined from zero to eighty percent reduction in detection rate, a range consistent with the partial, contested protection that multi-spectral camouflage and obscurants provide against automated detection (Su et al., 2023; Hwang & Ma, 2024; Dam Quang et al., 2022). The baseline detection rate lambda_0 is treated parametrically rather than asserted, since it depends on ISR density that varies by sector and day.

Three limitations are intrinsic and I prefer to state them at the outset. First, the loop time T_rs is an aggregate that hides real variance; a layered ISR-strike complex may present several loops of different lengths, and collapsing them to one number is a simplification I accept for tractability. Second, the detection process is modelled as memoryless with a constant rate, whereas real detection is bursty and conditioned on activity peaks such as boat launches and crane lifts; the constant-rate assumption is conservative in some phases and optimistic in others. Third, concealment effectiveness C is treated as a single scalar, though it is in truth spectrum- and sensor-specific, and a value that defeats visual recognition may not defeat thermal or radar sensing (Su et al., 2023; Chen et al., 2024). These constraints bound the claims the model can support.

RESEARCH RESULTS

The findings organise into three blocks aligned with the three hypotheses: the decomposition of exposure time and its compressibility; the behaviour of the reconnaissance-strike loop as the binding denominator; and the composite survivability surface that their ratio generates under varying concealment. They are presented here without interpretation, which follows in the analytical sections.

Total exposure time decomposes into three additive phases whose compressibility differs sharply. Assembly time is the most compressible, because modularity, prefabrication, and parallel multi-point emplacement move work off the critical path, and the accelerated-construction and production-scheduling literatures document order-of-magnitude on-site time reductions from exactly these methods (Azizinamini, 2020; Peiris et al., 2023; Embaby & El Naggar, 2024). Trafficking time is bounded below by load-rating and dynamic-response constraints, since vehicles must cross at spacings and speeds that keep pontoon motions and member stresses within limits (Miao et al., 2021; Chordà-Monsonís et al., 2023; Pinkney et al., 2022). Recovery time, the retrieval or abandonment of the bridging, is frequently neglected in planning yet adds materially to the window during which the site remains a target. Table 1 records the illustrative phase ranges used as model inputs.

Phase	Illustrative range (min)	Primary compressibility lever
Assembly (T_a)	15 – 90	modularity, parallel emplacement
Trafficking (T_t)	10 – 45	throughput vs. dynamic-load limits
Recovery (T_r)	5 – 15	pre-planned retrieval / abandonment
Total exposure (T_exp)	30 – 150	sum of the above

Table 1. Illustrative decomposition of total crossing exposure time into phases, with compressibility informed by the accelerated-construction and floating-bridge literatures. Values are model inputs, not field measurements.

The reconnaissance-strike loop occupies the denominator and behaves as a threshold rather than a smooth cost. Treated as an interval from first detection to delivered effect, it is estimated from the drone-warfare and simulation literatures to fall, in a contested sector, into the low tens of minutes, . tightening as one-way attack drones and pre-cued fires compress the sensor-to-shooter chain (Plichta, 2025; Drozd et al., 2021). Table 2 records the loop-time scenarios used in the model, expressed as planning assumptions rather than measured constants.

ISR environment	Loop time T_rs (min)	Character
Saturated / pre-cued	10	loitering munitions on call
Contested	20	responsive but finite tasking
Degraded / permissive	40	delayed tasking, EW friction

Table 2. Reconnaissance-strike loop-time scenarios used in the model, expressed as planning assumptions informed by drone-warfare and constructive-simulation studies (Plichta, 2025; Drozd et al., 2021; Lunsford & Bradley, 2021).

The composite survivability surface exposes the interaction the two preceding tables only imply. When total exposure is held below the loop time, the index falls to or beneath unity and modelled survival probability is effectively one, because the crossing completes before any detection can be converted into a strike. As exposure rises above the loop time, survival probability decays exponentially in the overhang, and concealment, by lowering the detection rate, flattens that decay. Across the parameter space, modelled crossing-survival probability ranges from below 0.10 for a 150-minute unconcealed crossing against a 10-minute loop to about 0.90 for a 30-minute, eighty-percent-concealed crossing against a 20-minute loop. Table 3 reports representative values.

T_exp (min)	T_rs (min)	CEI	Concealment C	P_cross
30	20	1.5	0%	0.61
30	20	1.5	60%	0.82
30	20	1.5	80%	0.90
90	20	4.5	0%	0.030
90	20	4.5	70%	0.35
20	20	1.0	0%	1.00
150	10	15.0	0%	0.001

Table 3. Illustrative Crossing Exposure Index and modelled survival probability P_cross for representative combinations of exposure time, loop time, and concealment (baseline detection rate lambda_0 = 0.05 per minute). All values are model-derived and require validation.

The pattern is consistent and, for the engineering question, decisive. Survival is governed first by whether exposure can be brought near or below the loop time, which is an assembly-and-sequencing problem, and second, in the regime where exposure unavoidably overhangs the loop, by the concealment-reduced detection rate, which is a signature problem. The worst outcomes combine a long exposure with a short loop and no concealment; the best combine a short exposure with meaningful concealment. The analytical sections explain why this ordering holds and what it implies for design.

THE RECONNAISSANCE-STRIKE LOOP AS THE BINDING TIME CONSTRAINT

The first and most consequential result is that survivability is set by a comparison, not by an absolute. A crossing is not safe because it is fast in some general sense; it is safe because it is faster than the particular adversary loop it faces. The drone-warfare literature is explicit that the decisive change of the present period is the compression of that loop. Mass one-way attack drones have turned detection into engagement at a tempo that older planning factors never assumed, and the campaign-level effect is to make any persistent concentration a wasting asset (Plichta, 2025). The attritional reading of the same war locates the centre of gravity in battlefield transparency: forces that can be seen for long enough are ground down, and the premium accordingly shifts to brevity of exposure (Gady & Kofman, 2024). Constructive simulation puts numbers behind the intuition, showing that even limited aerial reconnaissance markedly raises the probability that a protected force is located and engaged (Drozd et al., 2021).

Placing the loop in the denominator of the index is therefore not a modelling convenience but a statement about where the binding constraint lives. The survivability function P_cross = exp(−lambda · max(0, T_exp − T_rs)) has a discontinuity in its behaviour at CEI = 1 that no smooth cost function would capture. Below that point the overhang is zero and survival is certain in the model, because the crossing is complete before the loop can close; above it, survival decays. This threshold structure means that the marginal value of a minute saved is not constant. A minute saved while exposure still overhangs the loop buys an exponential improvement in survival; a minute saved once exposure is already below the loop buys nothing, because survival is already near one. The implication for engineering effort is immediate and is taken up in the next section.

The threshold also reframes a planning instinct that the doctrinal literature has only partly displaced. Site-selection optimisation, including the careful matching of water depth to crossing means (Sedláček & Dohnal, 2021) and the geoprocessing identification of feasible sites (Sedláček & Dohnal, 2024), implicitly treats the problem as static: find the best place and build there. Under a fast loop the question is no longer only where but how briefly, and a hydrographically inferior site that permits a shorter exposure may dominate a superior one that does not. The CEI does not replace site selection; it adds the temporal dimension that a transparent battlefield makes decisive, and it allows the two to be traded against each other in a common currency.

There is a limit to how far the loop can be lengthened by the crossing force itself, and honesty requires acknowledging it. Counter-reconnaissance and counter-UAS measures can degrade the adversary's sensing and lengthen T_rs, and standardised evaluation of such systems is maturing (De Cubber et al., 2025), but a competent opponent fields layered ISR with redundant paths, so the defender should not assume the loop can be stretched at will. The prudent planning posture treats T_rs as partly exogenous and concentrates controllable effort on the numerator, exposure time, and on the detection rate that concealment governs. The loop is the constraint one races against, not the one variable one controls.

ENGINEERING THE ASSEMBLY TIMELINE: MODULARITY, PARALLELISM, AND THROUGHPUT

If exposure is the controllable numerator, then assembly is the phase where engineering buys the most time, because it is the most compressible. The discipline of accelerated bridge construction exists to move work off the critical on-site path through prefabrication, standardised modules, and rapid connection (Azizinamini, 2020), and the material science that supports it, such as cost-effective ultra-high-performance concrete for prefabricated elements, has matured in parallel (Wang et al., 2021). Modular truss and double-truss systems have been characterised experimentally and analytically for the stability and capacity that fast field assembly demands (Embaby & El Naggar, 2025a; Embaby & El Naggar, 2025b), and the behaviour of their steel shear panels under load is now documented (Embaby & El Naggar, 2024). The lesson the present model draws from this body of work is quantitative: assembly time is not a fixed natural cost but an optimisation variable, and the literature reports the order-of-magnitude reductions that modularisation can deliver.

Parallelism is the lever the index rewards most, because the survivability payoff to compressing assembly is exponential while exposure still overhangs the loop. Production-scheduling research on modular construction shows that assembly time responds to sequencing and resource allocation, and that metaheuristic optimisation of those schedules yields substantial reductions (Peiris et al., 2023). Translated to the riverbank, this argues for emplacing bays at multiple points simultaneously and floating them together, for pre-assembling ramp and approach elements on the near shore before the gap is ever touched, and for staging components so that the critical path contains only the connections that must be made over water. Each of these moves attacks T_a, and each minute removed from T_a while CEI still exceeds one produces a disproportionate gain in modelled survival, as Table 3 shows in the contrast between the 90-minute and 30-minute rows.

Trafficking, by contrast, resists compression, and the floating-bridge literature explains why. The dynamic response of a pontoon bridge to moving vehicle loads is bounded by motion and stress limits that set maximum safe speeds and minimum spacings (Miao et al., 2021; Zhang & Li, 2021), the hydrodynamic interaction between pontoons conditions how the structure behaves as loads traverse it (Fenerci et al., 2022), and the dynamic load allowance of modular spans must be respected to avoid overstressing members (Chordà-Monsonís et al., 2023). Dynamic load testing of a modular truss bridge with actual military vehicles confirms that these are operational, not merely theoretical, limits (Pinkney et al., 2022). The planner cannot, therefore, simply drive the force across faster without limit; throughput is capped by structural dynamics, and beyond a point the only way to reduce trafficking exposure is to reduce the load that must cross or to add crossing capacity in parallel.

Recovery is the phase planning most often forgets, and the index insists it be counted. Exposure does not end when the last vehicle reaches the far bank; it ends when the bridging no longer presents a target, which means either rapid retrieval or deliberate abandonment. A crossing optimised for fast assembly and trafficking but left in place for an hour while crews attempt to recover valuable bridging has simply moved its vulnerability to the end of the timeline. The disciplined posture pre-plans recovery as a timed phase with its own resources, and in the highest-threat case accepts abandonment of the bridging as the survivable choice, trading materiel for the lives of the engineer force. This is an uncomfortable trade, but the model makes its logic explicit: when the loop is short, every minute of recovery is a minute of exponential risk.

CONCEALMENT AS A DETECTION-RATE MULTIPLIER, NOT A CLOAK

Once exposure cannot be driven below the loop time, survivability passes to the detection rate, and here the engineering question is not how to become invisible but how to become detected more slowly. The model expresses this through lambda = lambda_0 · (1 − C), in which concealment does not zero the detection rate but scales it, lengthening the expected time to detection and thereby the chance that the crossing finishes before a strike is cued. This framing matches what the detection literature shows is actually happening on the far side of the contest. Automated detection of vehicles and military targets from unmanned platforms is now fast and robust, including at low-altitude oblique perspectives (Zeng et al., 2024) and in real time from improved deep networks (Li et al., 2023), and the field has matured into comprehensive surveyed practice (Tang et al., 2023). Concealment that aims at invisibility against such systems will fail; concealment that aims at delay can still pay.

The multi-spectral character of modern sensing dictates that concealment be multi-spectral too, and the materials literature has moved in that direction. Infrared camouflage textiles now address the thermal band that defeats visual-only measures (Su et al., 2023), and broadband UV-visible-infrared treatments target the layered backgrounds of real surveillance (Hossain, 2024). The point is sharpened by the demonstration that deep-learning detectors can be trained specifically against camouflaged military objects with purpose-built datasets (Hwang & Ma, 2024) and that visible-thermal fusion with transformer architectures detects targets that defeat any single band (Chen et al., 2024). A crossing concealed only in the visible spectrum presents an undiminished thermal signature, and the model would credit it with a C near zero against a thermal-capable sensor. Effective C therefore requires attention to thermal management of engines, boats, and freshly disturbed earth as much as to visual pattern.

Obscurants occupy a special place in this logic because they reduce the detection rate of an entire area for a controllable interval rather than concealing a fixed object. Infrared-screening smokes, including red-phosphorus compositions, degrade optical and thermal sensing across a sector (Dam Quang et al., 2022), which in the model corresponds to a temporary, area-wide depression of lambda_0 itself. Their value is greatest exactly when exposure overhangs the loop and the crossing must survive a detectable window it cannot eliminate; a screen timed to the highest-signature phases, such as boat launches and crane lifts, buys precisely the slowed detection the survivability function rewards.

The cost is that obscurants are themselves a signature of activity, so their use must be weighed against the inference an alert adversary draws from smoke appearing on a likely crossing site.

The marginal value of concealment rises as exposure approaches the loop time, and this is the third hypothesis made quantitative. When CEI is well above one, even strong concealment cannot save a crossing whose overhang is large, because the exponential has too much argument to overcome; when CEI is near one, a modest reduction in detection rate can push survival from marginal to high, because the overhang is small and the exponential is sensitive. Table 3 shows the effect in the 30-minute rows, where raising concealment from zero to sixty percent lifts modelled survival from 0.61 to 0.82, against the 90-minute case where even seventy-percent concealment reaches only 0.35. Concealment, in other words, is most worth investing in precisely when the assembly engineers have already done their job and brought exposure close to the loop. The two levers are complements, not substitutes.

INTEGRATING EXPOSURE REDUCTION INTO A SURVIVABLE CROSSING ARCHITECTURE

The four results combine into an architecture rather than a checklist, and the architecture is ordered by the structure of the index. The first priority is to drive total exposure toward the loop time through assembly compression and disciplined recovery, because below CEI of one the model grants near-certain survival and no other measure is needed; the second priority, in the regime where exposure unavoidably overhangs the loop, is to lower the detection rate through multi-spectral concealment and timed obscuration; the third is to lengthen the loop itself where counter-reconnaissance permits, treated as a bonus rather than a foundation (De Cubber et al., 2025; Martinez et al., 2024). This ordering is not arbitrary preference; it follows from the exponential form of the survivability function — the overhang term dominates, and concealment merely modulates it.

Sequencing ties the levers together in time. Because detection is concentrated at activity peaks, the architecture schedules the highest-signature events into the protection of obscurants and low-visibility periods, disperses near-shore assembly so that no single observation captures the whole effort, and pre-positions and pre-conceals approach routes so that the detectable window opens as late as possible and closes as early as possible. Decoy crossing sites, which raise the adversary's targeting uncertainty and effectively dilute its loop across multiple candidates, are a low-cost complement consistent with the deception tradition the camouflage literature formalises (Su et al., 2023; Hossain, 2024). The aim throughout is to keep the detectable, strikeable window beneath the loop even when the physical occupation of the site cannot be.

The architecture must also respect the structural constraints that the bridging literature makes non-negotiable. Compression of the timeline cannot come at the price of exceeding dynamic-load limits during trafficking (Chordà-Monsonís et al., 2023; Pinkney et al., 2022), nor of an assembly so hurried that pontoon interaction or member stresses are mishandled (Fenerci et al., 2022; Huang et al., 2023). The survivable crossing is therefore not the fastest conceivable one but the fastest one that remains structurally sound, and the engineering judgment the model supports is the joint minimisation of exposure subject to those limits. A bridge that fails under load mid-crossing converts a survivability problem into a catastrophe, so speed is bounded by safety, and the index should be read as an objective to be optimised within that boundary, not against it.

Read together, the analytical strands answer the research question with more precision than a call for speed or stealth alone allows. A pontoon crossing survives persistent drone ISR when its total exposure is engineered toward or below the adversary reconnaissance-strike loop and its residual detectable window is suppressed by multi-spectral concealment and timed obscuration, with counter-reconnaissance lengthening the loop where it can. The CEI is the instrument that orders these efforts, telling the planner when speed has bought all it can and concealment must take over, and when concealment is wasted because the timeline has not yet been compressed. It converts a set of separately optimised disciplines into a single survivability calculus.

CONCLUSION

Wet-gap crossing under persistent unmanned surveillance is best understood not as a structural problem with a survivability complication but as a survivability problem with a structural constraint. This article set out to determine what governs whether a pontoon crossing survives, and where engineering effort should be spent, and the analysis supports an ordered rather than a diffuse answer.

The first hypothesis, that the binding constraint is the ratio of total exposure time to the reconnaissance-strike loop, and that driving exposure below the loop confers near-immunity to timely engagement, is confirmed within the model. The survivability function is flat at certainty while exposure stays under the loop and decays exponentially once it overhangs, so the Crossing Exposure Index, not assembly time considered alone, is the quantity that orders outcomes. A crossing faster than its adversary's loop completes inside the enemy's decision cycle; one slower than the loop lives or dies by how slowly it is detected.

The second hypothesis, that assembly-time reduction yields diminishing survivability returns once exposure exceeds the loop unless paired with concealment, is confirmed and given quantitative shape. While exposure overhangs the loop, every minute removed from assembly buys an exponential gain, which is why modularity and parallel emplacement are the first call on engineering effort (Azizinamini, 2020; Peiris et al., 2023; Embaby & El Naggar, 2024); once exposure is near the loop, further speed buys little and the detection rate becomes the operative variable. The two levers are complements whose ordering the index makes explicit.

The third hypothesis, that concealment acts as a detection-rate multiplier whose marginal value rises as exposure approaches the loop, is confirmed without qualification. Against automated multi-spectral detection (Hwang & Ma, 2024; Chen et al., 2024), concealment cannot deliver invisibility, but it can lengthen expected time to detection, and the model shows its effect is greatest precisely when the assembly engineers have brought exposure close to the loop. Multi-spectral camouflage and timed obscuration (Su et al., 2023; Dam Quang et al., 2022) are therefore the natural second tier of a survivable crossing, not a substitute for speed.

The principal original contribution of this article is the Crossing Exposure Index and its concealment-adjusted survivability function, which couple bridging-engineering timelines, concealment-modulated detectability, and the drone reconnaissance-strike cycle into one expression. To my knowledge this coupling has not been made before; the bridging, camouflage, and operations-research literatures each optimise one term in isolation. The index produces a single, teachable design rule, namely to compress exposure beneath the loop first and suppress the residual detection rate second, and it gives a planner a common currency in which to trade site quality, assembly method, and concealment against one another.

The limitations are real and I would rather name them than dress them up. The reconnaissance-strike loop is an aggregate that conceals real variance and layered ISR paths; the detection process is modelled as memoryless and constant-rate, whereas real detection is bursty around activity peaks; and concealment is reduced to a single scalar where it is in truth sensor- and spectrum-specific. Each is a boundary on the claims rather than a refutation of them. The natural next step is validation through field exercises and constructive simulation of the kind already applied to aerial reconnaissance (Drozd et al., 2021; Lunsford & Bradley, 2021), instrumented to measure real exposure phases and real detection rates against representative ISR, which would convert the model-derived survival probabilities into measured ones and, I suspect, sharpen rather than overturn the ordering proposed here. Until that work is done, the numbers in this article should guide reasoning, not procurement.

A closing reflection from the standpoint of military engineering rather than tactics. The river crossing has always been where engineering and enemy action meet most directly, and the drone has simply made the meeting faster and more visible. The contribution offered here is to give the engineer a way to think about that speed in the same breath as structure and signature, so that the next crossing is planned around the clock it must beat rather than around the bridge it must build.

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SKRAĆIVANJE VREMENA IZLOŽENOSTI PRI POSTAVLJANJU PONTONSKIH PRELAZA POD STALNIM ISR NADZOROM DRONOVA: INŽENJERSKA RJEŠENJA ZA BRZU MONTAŽU I MASKIRANJE OBALA

Gordana Simić

Univerzitet u Nišu,
Niš, Republika Srbija
E-mail: gordana.simic@masfak.ni.ac.rs

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Sažetak: Savladavanje vodenih prepreka postalo je jedan od najopasnijih inženjerskih zadataka na savremenom bojištu, jer je pontonski most velika, nepokretna i toplotno i geometrijski uočljiva struktura koja mora ostati na mjestu dovoljno dugo da snaga pređe, sve to pod stalnim bespilotnim izviđanjem. Ovaj rad postavlja usko pitanje: šta određuje da li prelaz preživi i gdje treba uložiti inženjerski napor da bi se smanjila izloženost koja ubija pontonirske jedinice? Istraživanje preokvirava preživljavanje kao trku dvaju satova. Prvi je ukupno vrijeme izloženosti mjesta prelaza, zbir montaže, prebacivanja snaga i povlačenja mosta; drugi je protivnikova izviđačko-udarna petlja, interval od prve detekcije do isporučenog dejstva. Originalni doprinos rada jeste indeks izloženosti prelaza (CEI), definisan kao odnos ukupnog vremena izloženosti i vremena izviđačko-udarne petlje, zajedno s funkcijom preživljavanja korigovanom maskiranjem, u kojoj vjerovatnoća dovršetka prelaza prije nego što udar stigne opada eksponencijalno s izloženošću koja prelazi protivnikovu petlju, skalirano stopom detekcije koju maskiranje smanjuje. Model daje oštro projektno pravilo, odsutno i u inženjerskoj i u operaciono-istraživačkoj literaturi: kada se izloženost spusti ispod vremena petlje, prelaz se dovršava unutar protivnikovog ciklusa odlučivanja i pravovremeno dejstvo postaje gotovo nemoguće, dok iznad tog praga preživljavanje naglo pada, a maskiranje, a ne dodatna brzina, upravlja ostatkom. Ilustrativni proračun za vremena montaže od 30 do 150 minuta, vremena petlje od 10 do 40 minuta i efikasnost maskiranja od nula do osamdeset posto daje modelirane vjerovatnoće preživljavanja prelaza od ispod 0,10 za spor i nemaskiran prelaz protiv brze petlje do iznad 0,90 za brz i dobro maskiran prelaz. Zaključuje se da je smanjenje izloženosti sistemski problem: modularna i paralelna montaža radi sažimanja vremena, upravljanje signaturom radi snižavanja stope detekcije i sekvenciranje radi održavanja uočljivog prozora ispod protivnikove petlje, pri čemu nijedno samo po sebi nije dovoljno. Sve numeričke vrijednosti izvedene su iz modela i zahtijevaju empirijsku i vježbovnu validaciju prije primjene.

Ključne riječi: *savladavanje vodenih prepreka, pontonski most, vrijeme izloženosti, ISR dronovi, izviđačko-udarna petlja, maskiranje i prikrivanje, vojno preživljavanje.*