

SAFETY FINDINGS

Safety as Access

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Findings

This paper extends the General Theory of Access by explicitly accounting for safety. Using a capability approach, we show how crash probability and severity systematically reduce lifecycle access via a severity-weighted impairment multiplier. The resulting safety-adjusted access can be monetised in appraisal, avoiding double counting relative to conventional Value of Statistical Life (VSL) methods.

1. Questions

Crashes reduce the ability to engage in desired activities; fatal crashes eliminate it. Cutting crash risk increases future access. This is not properly accounted for in current evaluations, undervaluing safety investments.

Access measures how easily opportunities can be reached for a given set of costs. Following Levinson and Wu (2020), access at a given origin depends on the spatial distribution of opportunities and the generalised costs required to reach those opportunities. This paper extends that formulation by explicitly accounting for safety, recognising that crashes can permanently impair or even eliminate an individual's ability to access opportunities.

How does safety, expressed through the probability and severity of crashes, systematically reduce lifecycle access? Specifically:

1. How can crash risk and severity be incorporated clearly and simply into lifecycle access measures?
2. How can these safety-adjusted access measures be monetised within an access-based appraisal framework, avoiding double counting that may arise with conventional Value of a Statistical Life (VSL) or Value of a Statistical Life-Year (VSLY) methods?

This paper introduces a novel multiplicative retention factor over the lifecycle, inspired by survival/hazard modelling, to reflect the carry-forward effect of safety impairment. Retention is defined as the proportion of original (potential) access that remains available to an individual after accounting for the cumulative probability and severity of crashes up to a given year. While similar multiplicative retention logic appears in demography and reliability, to

our knowledge it has not previously been applied to access. This framework isolates objective crash risks and impairment. Perceived safety, which may also suppress realised access, is important but not addressed here.

The *capability constraints* models of disability (Sen 1999; World Health Organization 2001; Mitra 2006; Burchardt 2004) view impairment as a lasting cut to achievable functionings due to personal, environmental, or social constraints. In transport terms, access, the set of spatially distributed activities an individual can reach, depends on capability. Crash-related impairments reduce capability by lowering achievable access, even when the network is unchanged. The retention factor approach below quantifies the share of baseline capability preserved after cumulative injury risks over the lifecycle.

2. Methods

Instantaneous access

The general access metric for origin i in year l is:

$$A_{i,l} = \sum_j g(\mathbf{O}_{j,l}) f(\mathbf{C}_{ij,l}),$$

where $\mathbf{O}_{j,l}$ is the number of opportunities at j in year l , $\mathbf{C}_{ij,l}$ is the generalised cost of travel from i to j , $f(\cdot)$ is an impedance function, and $g(\cdot)$ is an opportunity transform. This is measured at a single point in time, so it is worth denoting it as *instantaneous* access to distinguish it from the *lifecycle* measure.

When combined with safety, the generalised travel cost $C_{ij,l}$ must *exclude* crash-impairment terms (risk of death or lasting injury). Capability loss from crashes is handled solely by $\eta_{i,l}$ below, avoiding double counting when we later monetise access.

Lifecycle access

The expected lifecycle access, measured e.g. in access-years, can be written as:

$$\mathbb{E}[A_{i,\Lambda}] = \sum_{l=0}^L \Lambda(r, l) A_{i,l},$$

with a typical discount factor:

$$\Lambda(r, l) = (1 + r)^{-l},$$

which reflects time preference or opportunity cost (Levinson and Wu 2020).

Safety impairment

Safety impairment is a lasting reduction in achievable access caused by crash injury. We encode impairment by severity-specific capability retention factors $\kappa_s \in [0, 1]$, which propagate through a lifecycle retention process $\eta_{i,l}$. Let κ_s be the long-run capability *retained* after a crash severity of s : $\kappa_{\text{PDO}} = 1$ (property-damage-only, no long-term effect), $\kappa_{\text{fatal}} = 0$ (fatal, no future access), and $0 < \kappa_{\text{serious}} < 1$ (partial impairment).

Safety adjustment

Let $q_{l,s}$ be the individual (or cohort-average) probability of a crash of severity $s \in \{\text{PDO}, \text{serious}, \text{fatal}\}$ in year l , *conditional on no prior impairment or fatality* (i.e., conditional on having retained access up to year l).

For the example below we treat $q_{l,s}$ as metro-wide, but the method allows location-varying $q_{i,l,s}$.

The cumulative retention at i for year l is:

$$\eta_{i,l} = \prod_{\tau=0}^{l-1} \left(1 - \sum_s q_{\tau,s} (1 - \kappa_s) \right), \quad \eta_{i,0} = 1. \quad (1)$$

The multiplicative structure in Equation 1 ensures that retention in year l is conditional on having retained access in all previous years, mirroring the survival function in hazard modelling. In this context, ‘survival’ means avoiding a crash that causes partial or total loss of access. Once access is lost due to impairment, it is not recovered in subsequent years, so earlier crashes compound over the lifecycle. This is distinct from $\Lambda(r, l)$, which down-weights the *value* of future access regardless of capability, whereas $\eta_{i,l}$ adjusts the *quantity* of access available. Severities within a year are treated as mutually exclusive, so that $\sum_s q_{l,s}$ equals the total crash probability in year l . We assume at most one crash outcome per year, and independence of yearly hazards given survival; finer time steps, or continuous-time hazards, can relax these assumptions.

Safety-adjusted expected lifecycle accessibility

The safety-adjusted expected lifecycle accessibility is:

$$\mathbb{E}[A_{i,\Lambda,\eta}] = \sum_{l=0}^L \Lambda(r, l) (\eta_{i,l} A_{i,l}). \quad (2)$$

Valuation

Property markets capitalise access into prices. We estimate a hedonic equation to recover a marginal willingness-to-pay per access-year, (Mann and Levinson 2024):

1. **Estimate hedonic:** Using observed property transactions (or rents), estimate

$$P_i = \alpha + \beta \mathbb{E}_{\text{base}}[A_{i,\Lambda,\eta}] + X_i' \gamma + \varepsilon_i,$$

where P_i is the price (or rent) of parcel i , β maps a change in safety-adjusted lifecycle access into a price change, holding other controls X_i constant, (interpreted per parcel, per person, or per m^2 depending on specification) for the base, historical level of safety.

2. **Intervention:** For a safety change, update the crash probabilities $q_{l,s}$ in Equation 1, recompute $\eta_{i,l}$, calculate $\mathbb{E}_{\text{after}}[A_{i,\Lambda,\eta}]$, and then

$$\Delta P_i \approx \beta (\mathbb{E}_{\text{after}}[A_{i,\Lambda,\eta}] - \mathbb{E}_{\text{base}}[A_{i,\Lambda,\eta}]).$$

Because β is estimated from prices that already capitalise baseline safety, adding a separate VSL/VSLY term to the same risk change would count the same benefit twice; in this framework, risk enters once through η , and is monetised once through β .

3. **Aggregation:** Sum $\sum_i \Delta P_i$ for the total change in property value in the study area.

$$\mathbb{B} = \sum_i \Delta P_i.$$

Divide by population or occupancy to express per-person effects if desired.

Interventions are valued by re-running the same access calculation under new crash risk inputs, avoiding double counting relative to conventional VSL/VSLY methods. The mapping $\Delta P_i \approx \beta \Delta \mathbb{E}[A_{i,\Lambda,\eta}]$ is a first-order, partial-equilibrium estimate; large uniform safety changes may alter β or induce sorting.

Mobility aids

Rehabilitation or assistive technologies (e.g., better wheelchairs) can be represented as higher κ_{serious} (more capability retained after injury).

Table 1. Input parameters and implied per-year retention multipliers

Parameter	Before	After
q_{serious}	0.020	0.015
q_{fatal}	0.010	0.005
κ_{serious}	0.700	0.700
Per-year retention multiplier	0.984	0.9905
$\eta_{i,l}$ uses $[1 - q_{\text{serious}}(1 - \kappa_{\text{serious}}) - q_{\text{fatal}}]$.		

Table 2. Safety-adjusted lifecycle access: before vs. after.

Year	Discount	Retention		Discounted, retained access		Diff.
l	$\Lambda(r, l)$	$\eta_{i,l}$		$\Lambda(\eta_{i,l}A_{i,l})$		
		Before	After	Before	After	After-Before
0	1.000	1.000	1.000	100.000	100.000	0.000
1	0.952	0.984	0.991	93.714	94.333	0.619
2	0.907	0.968	0.981	87.824	88.988	1.164
$\mathbb{E}[A_{i,\Lambda,\eta}]$		–	–	281.538	283.321	1.783

Note: Per-year values are $\Lambda(r, l) \eta_{i,l} A_{i,l}$ from Eq. 2; $A_{i,l} = 100$.

3. Findings

Illustrative Example

To illustrate the method, consider an example with a three-year horizon ($l = 0, 1, 2$) with a discount rate of $r = 0.05$, giving discount factors $\Lambda = \{1.000, 0.952, 0.907\}$. Baseline access is fixed at $A_{i,l} = 100 \quad \forall l$. Parameters ($q_{\text{serious}}, q_{\text{fatal}}, \kappa_{\text{serious}}$) were selected to make the compounding arithmetic transparent rather than to represent a place, period, or cohort.

[Table 1](#) summarises key parameters in the before and after cases, and the implied per-year retention multipliers for the before and after cases.

[Table 2](#) summarises the results for the before and after safety improvement cases.

The improved safety case raises three-year discounted safety-adjusted access per person from 281.538 to 283.321 access-years, a change of $\Delta\mathbb{E} = 1.783$ access-years.

Suppose a hedonic regression yields $\beta = \$1,000$ per access-year per dwelling. Then

$$\Delta P_i \approx \beta \cdot \Delta\mathbb{E} = 1,000 \times 1.783 = \$1,783 \text{ per dwelling.}$$

If the study area contains 1,000 dwellings, the aggregate benefit is

$$\mathbb{B} = 1,000 \times 1,783 = \$1,783,000.$$

This example shows how reductions in crash probabilities, applied over time, produce measurable gains in safety-adjusted lifecycle access. When combined with a hedonic estimate of β , these access gains translate directly into monetary values consistent with observed market behaviour, avoiding double counting relative to conventional VSL or VSLY methods.

Relation to time and money terms

In a conventional generalised cost, time and money enter $C_{ij,l}$ directly. In our framework, crash risk affects expected capability via $\eta_{i,l}$ rather than $C_{ij,l}$. Mixing capability-reducing risk disutility inside $C_{ij,l}$ while also monetising via β would double count.

Implications

First, any rise in crash probability cuts expected lifecycle access in all later years. Second, shifting probability from severe (fatal or serious) to less severe (PDO) crashes improves access, even if total frequency is unchanged. Third, adding safety to the access framework enables consistent, transparent valuation in appraisal, provided the generalised travel cost in $A_{i,l}$ excludes crash-impairment costs to avoid double counting effects already capitalised into prices. Here, the safety term reflects only capability loss not already embedded in the travel-cost metric. The hedonic-based β captures the internalised share of crash-related money costs (e.g., some medical, carer, or productivity impacts) to the extent they affect willingness to pay for location. External costs on other parties (e.g., public health systems, insurers, third parties) are not captured unless added elsewhere. Related methods could value capability differences more broadly, or losses from other life-course or network changes. Mode-specific comparisons require jurisdiction-specific data and are left to future work.

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