ANALYSIS OF MINIMUM DISTANCE FOR SPEED-LIMIT SIGN PLACEMENT

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Abstract: Traffic safety represents a major engineering and societal challenge, in which traffic control systems, including traffic signals and signs, are essential components of modern road infrastructure. In this context, the location of speed limit signs plays a key role in ensuring timely driver reaction and safe speed adjustment. Speed limit signs are only effective if the driver can perceive the sign, react, and adapt speed before reaching the enforcement point or the beginning of the regulated zone. This paper proposes a simple physics-based model that relates human reaction time and achievable longitudinal acceleration (deceleration) to the minimum required distance, $d_{\min.}$, for speed transitions between two limits. A case study is presented for a transition from $60km/h$ to $50km/h$, together with sensitivity results demonstrating how $d_{\min.}$ increases when reaction time is longer, or braking is weaker. The model provides practical guidance for the placement of speed limit and warning signs to enhance road safety and traffic control.

Keywords: *Road Safety*, *Traffic Control*, *Speed limit signs*, *Reaction time*, *Minimum Distance*

1. INTRODUCTION

Speed management is one of the most direct tools for reducing crash risk and severity across global transportation networks (World Health Organization, 2023; Evans, 2004). Nevertheless, speed limits and traffic control are effective only when drivers can comply with posted limits in real driving conditions (Federal Highway Administration, 2023; Pline, 2001). A typical compliance scenario is a speed-limit transition: for example, a driver travels at $60km/h$ and encounters a $50km/h$ sign before entering a settlement, school zone, or an enforcement location. In that moment, the driver needs time to perceive the sign, interpret it, decide to act, and then physically change speed. If the sign is placed too close to the regulated zone boundary, the driver may be unable to reach the new speed in time even with correct intentions, which reduces the effectiveness of traffic control and can increase risk.

Because the compliance problem is strongly time-and-distance dependent, it can be treated with elementary kinematics (Serway and Jewett, 2018; Young and Freedman, 2020). Beyond mechanical deceleration, driver recognition is fundamentally bounded by the legibility distance $(d_{\text{leg.}})$, which depends on sign character high (h) and that the observer's threshold visual angle (α) (Dewar and Olson, 2007; Koppa, 2001). When adverse environmental factors, such as night glare, for or cognitive load, the visual angle increases, bit the legibility distance collapses, severely compressing the road space available for safe deceleration (Urquhart and Young, 2021; Greenlee et al., 2018).

To resolve these operational conflicts, this paper introduces a unified mathematical formulation for the minimum distance $(d_{\min.})$ required for a driver to complete a speed change from an initial speed (v_1) to a target speed (v_2) after first recognizing a speed-limit sign, building upon foundational physical principles in traffic engineering (Naumovski and Koltovska Nechoska, 2025). The formulation explicitly incorporates human perception-reaction a reaction time (t_r) (Olson, 1972; Fambro et al., 1998) and a representative comfortable longitudinal acceleration (a) (negative for braking) or as it is named a deceleration magnitude (Garber and Hoel, 2019; Mannering and Washburn, 2020).

Furthermore, a step-by-step design algorithm is established to evaluate whether standard boundary placement satisfies $d_{\text{leg.}} \geq d_{\min.}$ or if additional advance signage and recommended safety buffers (d_b) are structurally required for robust road compliance (AASHTO, 2018; Federal Highway Administration, 2023). A practical case study ($60km/h$ to $50km/h$) alongside parametric sensitivity graphs, tables and figures, is used to demonstrate the real-world application, design insights and engineering implications of the proposed framework without introducing unnecessary complexity.

2. DRIVER PERCEPTION AND REACTION

○ Recognition point and legibility distance

In this model, time starts at the recognition point: the moment when the driver can reliably read the sign and understand the required speed limit. Recognition depends on visibility conditions (weather, lighting, glare), the driver's visual acuity and workload, and on the size and contrast of the numerals. A simple geometric approximation relates the legibility distance $(d_{\text{leg.}})$ to the numeral height (h) and the minimum visual angle (α) required for reading (Dewar and Olson, 2007):

$$d_{\text{leg.}} = \frac{h}{\tan \alpha} \tag{1}$$

Relation (1) is a physics-based proxy for the fact that a sign is not instantly readable at any distance. If the sign becomes readable only at a short distance, then the effective distance available for speed adjustment is reduced. For conservative traffic design, it is therefore useful to test whether $d_{\text{leg.}}$ is large enough to cover the required speed-transition distance (AASHTO, 2018).

While this trigonometric model provides an elegant, physics-based foundation, a comprehensive engineering framework must account for real world environmental and physiological complexities that dynamic visual processing introduces (Olson, 1996; Zwahlen and Schnell, 1999). In practice, the visual angle (α) is far from a static physiological constant. Visual acuity varies widely across many conditions: driver demographics, heavily influenced by age-related vision degradation (Urquhart and Young, 2021), atmospheric scattering such a fog, precipitation or haze and ambient illumination which means daylight versus night driving. Furthermore, dynamic visual acuity decreases nonlinearly as vehicle speed (v_1) increases due to the natural narrowing of the driver's peripheral visual field, a phenomenon known as tunnel vision, and reduced fixation durations on lateral infrastructure (Zwahlen and Schnell, 1999). Beyond static optical resolution, visual legibility is fundamentally constrained by contrast ratios retro reflectivity standards and cognitive visual workload. Modern traffic sign design relies on micro-prismatic retro reflective sheeting to maintain contrast under low-beam headlight conditions. However, environmental degradation, dew accumulation or severe headlight glare from oncoming traffic can severely attenuate contrast effectively increasing the required visual angle (α) and reducing $d_{\text{leg.}}$ (Dewar and Olson. 2007).

Additionally, in high-density urban environments, cognitive workload and visual clutter: commercial signage, complex signalization, or surrounding vehicle movements induce visual search delays (Urquhart and Young, 2021; Greenlee et all., 2018). In these scenarios, the driver does not instantaneously register the sign upon entering its optical legibility zone. Instead, detection is gated by visual search latency, effectively shortening the real legibility envelope. To bridge this gap in conservative infrastructure design, $d_{\text{leg.}}$ must be treated not merely as an idealized optical upper bound, but as a dynamic design variable bounded by worst-case environmental and human factor constraints (Koppa, 2001; Pline, 2001). Ensuring that $d_{\text{leg.}}$ substantially exceeds the required speed-transition distance provides an indispensable safety margin, preventing sudden emergency barking manoeuvres at zone entry points.

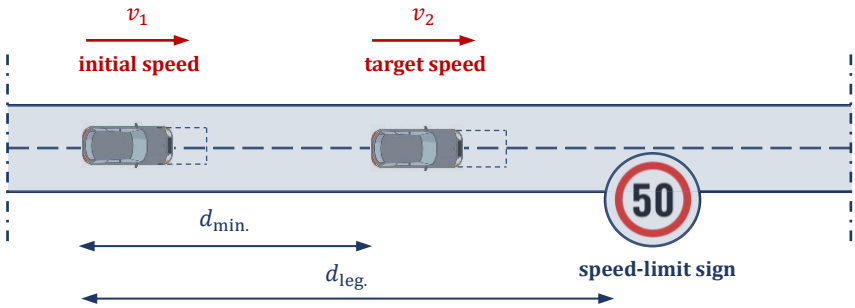


Figure 1. Sign-spacing schematic: recognition occurs before the sign, compliance requires $d_{\text{leg.}} \geq d_{\text{min.}}$.

○ Reaction time and reaction distance

Reaction time (t_r) is defined as the time interval between recognizing the speed-limit instruction and the driver initiating a control action (brake or accelerator). During t_r the vehicle approximately maintains its initial speed v_1. The travelled distance in this interval is the reaction distance (d_r), shown trough relation (2).

$$d_r = v_1 \cdot t_r \tag{2}$$

Reaction time is not constant across all drivers and situations. It increases under high cognitive load (distraction), low visibility, or fatigue (Greenlee at al., 2018; Hancock and Parasuraman, 1992). For the design-oriented calculations in this paper, t_r is treated as a constant representative value. Its variability is later addressed with safety buffers and sensitivity analysis.

To enrich the theoretical depth of the model, the reaction time (t_r) must be decomposed into its classical human factor components, traditionally categorized under the Perception Reaction Time (PRT) framework (Olson, 1972; Fambro et al., 1997):

1. Detection: The neuro-optical detection of the object within the visual field.
2. Identification: The cognitive processing required to read and comprehend the numerical speed limit.
3. Decision: The executive decision-making process to select an appropriate control response.
4. Response/ Movement: The neuromuscular execution of shifting the foot from the accelerator to the brake pedal, which means the physical pedal action.

While standard design guidelines often treat t_r as a deterministic baseline, typically ranging between $1.0s$ and $1.5s$ for nominal conditions or $2.5s$ for conservative AASHTO stopping sight distance calculations (AASHTO, 2018; Garber and Hoel, 2019), real-world behaviour exhibits significant stochastic variability (Fambro et al., 1998; Olson, 1996). Factors such as driver cognitive fatigue, age, alcohol impairment and secondary task distraction as smart phone usage or infotainment interaction, can cause t_r to spike well beyond nominal parameters (Hancock and Parasuraman, 1992; Greenlee et al., 2018).

Furthermore, approach speed (v_1) acts as a critical multiplier in (2). At higher approach speeds, even minor additions to t_r yield substantial expansions in reaction distance (d_r), severely consuming the physical road space available for actual barking (Mannering and Washburn, 2020).

While treating t_r as a representative constant, it simplifies baseline design calculation, so the robust theoretical framework must account all existed statistical distributions. It means that sensitivity analyses and safety buffers (d_b) are essential tools to ensure that sign placement accounts for high-percentile PRT values (e.g., 85th to 95th percentile drivers), thereby protecting vulnerable or impaired operators from entering speed reduction zones at unacceptably high speeds (Fambro et al., 1997; AASHTO, 2018).

○ Assumptions for longitudinal acceleration

The second driver-dependent component is longitudinal acceleration (or deceleration). For braking, the maximum available deceleration depends on tire-road friction, brake condition, and driver behaviour (Garber and Hoel, 2019; Mannering and Washburn, 2020). In many real situations a driver will not brake at the physical limit, but will apply a comfort deceleration. Therefore, the analysis assumes a constant deceleration magnitude of a, chosen to represent typical or conservative conditions. The purpose is not to model every detail of braking dynamics, but to quantify how braking capability translates into minimum compliance distance (Naumovski and Koltovska Nechoska., 2025).

While assuming a constant value for a, it serves as a robust proxy for macroscopic traffic modelling, a deeper physical analysis highlights several dynamic complexities in real-world barking profile applications (Serway and Jewett, 2018):

- **Jerk limits:** Deceleration does not step instantaneously from 0 to a. Instead, it follows a transient ramp-up phase governed by jerk limits, which means the time rate of change of deceleration, which reflects the mechanical pressure build-up in the hydraulic barking system and the driver's gradual pedal application.
- **Road grade and micro and macrotexture**: Grade resistance alters the effective longitudinal acceleration (AASHTO, 2018). Downgrades reduce effective braking efficiency, while upgrades assist in deceleration. Additionally, macro and microtextured of the pavement surface, pavement wear and wet surface conditions

reduce available friction, forcing driver to adopt lower comfort deceleration rates to maintain a lateral vehicle stability (Garber and Hoel, 2019).

- **Vehicle heterogeneity:** Heavier commercial vehicle (e.g., multi-axial trucks) exhibits substantially different barking dynamics, longer brake system response delays and lower thresholds for thermal brake fade compared to passenger cars (Mannering and Washburn, 2020).

By standardizing a to a conservative comfort limit, the algorithm ensures that the computed minimum speed transition distance ($d_{\min.} = d_r + d_c$) reflects an effortless, comfortable speed transition for the vast majority of the vehicle fleet. This approach prevents comfortable deceleration profiles from deteriorating into harsh, emergency braking events at zone boundaries.

3. SPEED TRANSITION MODEL

○ Deceleration from v_1 to v_2 $(v_1 > v_2)$

After the reaction interval, the driver decelerates the vehicle with an assumed constant deceleration magnitude (a) ($a > 0$ in magnitude). The distance needed to reduce speed from v_1 to v_2 follows from the kinematic relation:

$$v_2^2 = v_1^2 - 2ad_c \tag{3}$$

Solving relation (3) for the speed-change distance (d_c), it gives:

$$d_c = \frac{v_1^2 - v_2^2}{2a} \tag{4}$$

The total minimum distance from recognition to the enforcement point (or zone boundary) is therefore the sum of the reaction distance and the speed-change distance:

$$d_{min} = v_1 t_r + \frac{v_1^2 - v_2^2}{2a} \tag{5}$$

○ Acceleration from v_1 to v_2 $(v_2 > v_1)$

If a driver accelerates after a sign that permits a higher speed, the same structure applies. Assuming a constant acceleration (a_{acc}), the minimum distance becomes:

$$d_{min} = v_1 t_r + \frac{v_2^2 - v_1^2}{2a_{acc}} \tag{6}$$

○ Design condition for sign placement

If the regulated zone begins at a fixed point and a sign is installed at that point, then the available distance for speed adjustment is approximately the legibility distance $(d_{\text{leg.}})$ (from the moment the sign becomes readable). A sufficient condition for physical compliance is:

$$d_{\text{leg.}} \geq d_{\min.} \tag{7}$$

If (7) is not satisfied, the sign should be placed upstream (earlier), or an advance warning sign should be used so that recognition occurs earlier (Federal Highway Administration, 2023; Pline, 2001). A practical approach is to include an additional buffer distance (d_b) to cover variability in reaction time, road friction, and comfort braking. The recommended placement distance is then:

$$d_{\text{req.}} = d_{\min.} + d_b \tag{8}$$

○ Step-by-step design algorithm

To translate the theoretical model into practical engineering practice, the step-by-step design algorithm offers structured, six-stage procedure for optimizing traffic sign placement and enhancing road compliance. By systematically comparing the physical deceleration spital requirements $(d_{\min.})$ against human visual legibility $(d_{\text{leg.}})$, the methodology ensures that the driver is provided with sufficient time and distance to adjust the speed smoothly. Ultimately, incorporating a safety buffer distance (d_b) into this decision-making framework converts baseline physical compliance into a robust, real-world traffic safety and control solution.

1. Choose the initial and target speeds (v_1, v_2) according to the approach speed and the posted limit.
2. Select a representative reaction time (t_r) and a conservative (or comfort) deceleration magnitude (a).
3. Compute $d_{\text{min.}}$ using (5).
4. Estimate legibility distance $(d_{\text{leg.}})$ (field observation or (1) as a conservative estimate).
5. If $d_{\text{leg.}} \geq d_{\text{min.}}$, the sign at the zone boundary can support compliance. Otherwise, place an advance sign so that recognition occurs at least $d_{\text{min.}}$ before the boundary.
6. Add a buffer (d_b) to obtain a recommended distance $(d_{\text{req.}})$ for robust compliance.

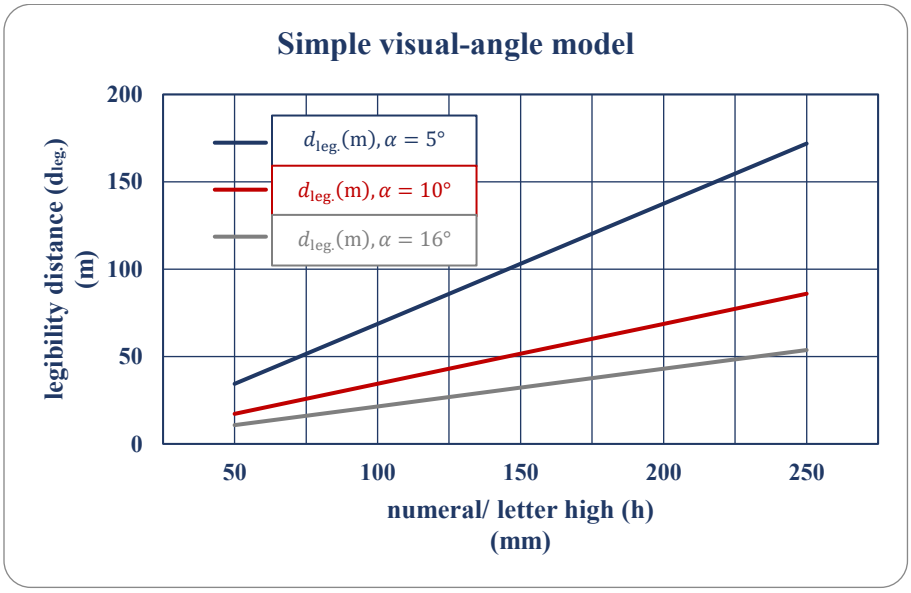


Figure 2. Example legibility distances for different numeral heights and threshold visual angles.

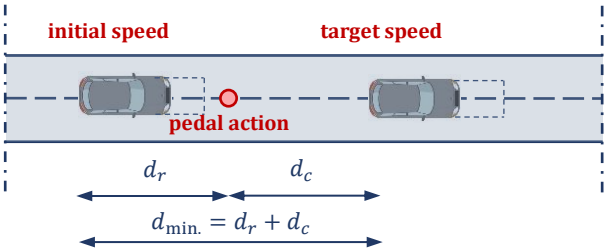


Figure 3. Speed profile from $60km/h$ to $50km/h$ with reaction and constant deceleration**.**

Figure 2. represents an important relationship between visual threshold limits and physical barking envelopes that is defined by tension of both human optical limits and vehicle kinematics (Olson, 1996; Zwahlen and Schnell, 1999). By plotting legibility distance $(d_{\text{leg.}})$ against character high (h), across three distinct threshold visual angles (α), Figure 2. maps the type of the driver through this important relationship at all. Essentially the visual angle (α) represents the minimum size a target must project onto the retina to be resolved by the driver's eye, but its distinction, as it is shown on Figure 2., distinguishes the driver into three different types.

- **The Optimal Observer $(\alpha = 5°)$ - dark blue curve on the graph, shown in Figure 2.**

Imagine a young driver with bright eyesight navigates a vehicle under ideal conditions (crisp, midday sunlight with a clean windshield and optimal atmospheric clarity). This driver, essentially, represents the optimal visual threshold curve, where the visual angle is $\alpha = 5°$. The physical meaning of this curve is dedicated to the driver's visual system that possesses exceptional spatial frequency resolution. It means that the eye of the driver can easily resolve minute details from a distance, meaning the sign's glyphs subtend a very small, sharp angle on its retina. As the driver approach the speed reduction zone, a standard $250mm$ numeral from a generous distance of approximately $175m$ can be clearly deciphered (Dewar and Olson, 2007). When this visual head-start is mapped against the kinematic requirements, shown in Figure 3., it becomes clear that driver's visual detection envelope far exceeds the physical space needed to slow down. The driver perceives the upcoming restriction long before the action is needed. It has truly ample time for the information, during the reaction phase (d_r), to

be processed smoothly by executing the pedal action at the exact moment of physical necessity and comfortably coasting through the deceleration phase (d_c) to transition seamlessly from v_1 to v_2 by the driver clearly.

- **The Standard Observer ($\alpha = 10°$) - dark red curve on the graph, shown in Figure 2.**

Now, for a clearer representation of the problem, a more common scenario is considered: An Average driver commuting home at dusk or navigating through light, persistent rain. Under this typical, slightly degraded conditions, the driver's visual acuity naturally drops, shifting the performance to the median curve where the threshold visual angle doubles to $\alpha = 10°$ (Dewar and Olson, 2007). For this type of driver, the sign's character heigh must project a larger image onto the retina before the brain of the driver can reliably decode its meaning. As the vehicle moves forward, the speed sign remains a blurry, unreadable shape until the driver closes the distance to roughly $85m$, assuming the same $250mm$ character high. Discussing the numbers, from an approximately tripled divided distance, this type of driver can easily decode a character of $75mm$ which is the standard heigh for small (lowercase) characters on traffic signs. This significantly compresses the driver's available safety window. While there is still enough physical road for comfortably slowing down, the margin for error has shrunk. The moment the traffic sign becomes legible, the driver must quickly transit to cognitive processing to physical barking. Any distraction during this shortened reaction distance (d_r) will directly eat into the physical deceleration distance (d_c), forcing a more aggressive brake application than originally intended (Urquhart and Young, 2021).

- **The Impaired od Adverse Observer ($\alpha = 16°$) - dark red curve on the graph, shown in Figure 2.**

Finally, picture a driver operating under severe visual constraints. This could be an older driver with significantly reduced visual sensitivity, or any driver battling adverse environmental conditions like dense, heavy fog, blinding glare from a low-lying sun or a severely dirty windshield (Dewar and Olson, 2007; Greenlee et al., 2018). These harsh conditions degrade contrast to the point that the driver's threshold visual angle balloons to a steep $\alpha = 16°$. Unfortunately, under this hostile optical conditions, the driver's visual recognition distance completely collapses. Even with a large $250mm$ character high on the sign, the driver cannot resolve numerical message until the are a mere $55m$ away. It can be namely concluded that this is where human physiology collides dangerously with the physical laws of vehicle kinematics.

As it is shown on Figure 3., a safe and comfortable deceleration path ($d_{\text{min.}}$) from $60km/h$ to $50km/h$ might physically require $60m$ of road to account for reaction time and smooth deceleration. Because this driver's legibility distance $(d_{\text{leg.}} = 55m)$ is shorter than minimum physical stopping distance ($d_{\text{min.}} = 60m$), the physical point of no return, before the speed limit sign can be read, will be crossed. By the time the sign becomes legible, a safe, comfortable deceleration is mathematically impossible. In this case, the driver is forced to choose between executing a jarring, emergency barking maneuverer or blowing past the speed boundary at an unsafe, non-compliant speed.

To mitigate these critical visual failures and regain a safety margin under elevated threshold angles, the driver must proactively modify their operating behaviour rather than relying solely on infrastructure design. To counteract a collapsing legibility distance, the most effective strategy in conscious, pre-emptive reduction in initial speed (v_1) when entering low-visibility conditions. By dropping driver's approach speed before encountering hazard zone, the driver fundamentally alters the vehicle kinematics illustrated in Figure 3.

Lowering the initial speed exponentially decreases both the reaction distance (d_r) and the mechanical barking run (d_c), thereby shrinking the required physical minimum distance ($d_{\text{min.}}$). This deliberate behavioural adjustment recalibrates the safety equation: even if an adverse visual angle ($\alpha = 16°$) delays traffic sign recognition until the vehicle is mere meters away. The drastically shortened stopping envelope ensures the driver can still achieve the target speed (v_2) safely and comfortably without triggering an emergency braking crisis.

Ultimately, overcoming degradation in sign legibility requires a synergistic framework where proactive behavioural adaptations interact directly with infrastructure placement parameters. By aligning individual driver foresight with scientifically derived minimum distance, achieving traffic system robust compliance and maintain safety margins even under severe visual constraints.

4. CASE STUDY: $60km/h$ TO $50km/h$

This section applies the proposed model to a common transition from $60km/h$ to $50km/h$. The goal is to determine the minimum distance from the recognition point to the beginning of the $50km/h$ zone such that the driver can reach $v_2 = 50km/h$, as a target speed. To validate the theoretical framework coupling human visual perception with vehicle kinematics, this case study is quite enough serious in showing a common speed reduction scenario: a transition from an exact initial speed ($v_1 = 60km/h$) to the target one ($v_2 = 50km/h$). This specific transition is highly representative of traffic zones marking entry into urban settlements or built-up environments, where timely compliance is critical for pedestrian and traffic safety (World Health Organization, 2023; Naumovski and Koltovska Nechoska, 2025). The assumed parameters, i.e. the permanent input in this case study, are $t_r = 1.2s$ and $a = 2.5m/s^2$.

Table 1. Case-study parameters and results.

Parameter	Value
Initial speed (v_1)	60km/h (16.67m/s)
Target speed (v_2)	50km/h (13.89m/s)
Reaction time (t_r)	1.2s
Deceleration magnitude (a)	2.5m/s^2
Reaction distance ($d_r = v_1 \cdot t_r$)	20m
Speed-change distance (d_c)	17m
Minimum distance ($d_{\text{min.}}$)	37m

○ Kinematic parameters in terms of baseline requirements

The mathematical model, behind this case study, incorporates realistic operational variables to establish a conservative baseline for driver's behaviour (Garber and Hoel, 2019). It means that the assumed parameters such as the driver's reaction time ($t_r = 1.2s$) is fixed, which accounts for cognitive perception, processing and the physical execution of the pedal action (Olson, 1972; Fambro et al., 1998). Assuming the deceleration magnitude ($a = 2.5m/s^2$) causes reflect steady and non-emergency braking, so the driver can take the control of any unconditional scenarios at all. Based on these inputs, the kinematic requirements are partitioned into two distinct phases as detailed in Table 1.:

1. Reaction distance (d_r): During the initial processing phase, the vehicle covers a distance of $20m$ at a constant initial speed (v_1), shown on Figure 3.
2. Speed-change distance (d_c): Upon brake engagement, the vehicle requires an additional $17m$ to smoothly drop its speed by $10km/h$, also shown on Figure 3.

Using (5), the computed minimum distance is $d_{\text{min.}} \approx 37m$ by aggregating the two distances obtained from each of the distinct phases correctly. This value has a clear interpretation: if the driver first recognizes the $50km/h$ instruction at least $37m$ before the zone entry, then the driver can reduce speed from $60km/h$ to $50km/h$ in time under the assumed comfort braking. If recognition occurs later (due to reduced visibility, glare, or small/dirty signs), compliance becomes physically difficult and the effective speed at the zone entry may remain above $50\ km/h$. To connect the result to sign placement, consider a road segment where the $50km/h$ zone begins at a specific boundary (e.g., start of a settlement). If the sign is placed exactly at the boundary, then recognition will typically occur upstream at the legibility distance $(d_{\text{leg.}})$The design check (7) requires $d_{\text{leg.}} \geq 37m$. If the expected $d_{\text{leg.}}$ is smaller, the sign should be moved upstream or an advance sign should be installed so that recognition occurs earlier (Federal Highway Administration, 2023).

○ Speed-sign placement through clear engineering implications

The practical utility of this case study lies in its direct correlation with geometric sign design and placement standards. It can be correctly identified that the standard boundary-line sign placement relies on an idealized operational assumption – specifically, that the expected legibility distance $(d_{\text{leg.}})$ Afforded by the sign's font heigh (h) and prevailing environmental conditions will meet or exceed the $37m$ physical threshold $(d_{\text{leg.}} \geq 37m)$.

However, under non-ideal scenarios where the visual threshold angle (α) increases due to poor ambient lightning, heavy glare, adverse weather or obstructed signs, the legibility distance collapses linearly, as characterized in the preceding visual-angel models. If $d_{\text{leg.}}$ Drops below the required $37m$ threshold, boundary placement becomes structurally defective. In this situation the driver will cross the physical point of necessary deceleration before deciphering the sig, resulting in speed non-compliance at the zone boundary or sudden, erratic braking manoeuvres that increase rear-end collision risks.

Consequently, this case study underscores a vital engineering principle:

Traffic sign placement cannot be decoupled from environmental and human physiological limits.

When localized conditions or vehicle speeds demand an envelope larger that standard visual legibility range, the design algorithm necessitates moving the regulatory sign further upstream or deploying advance warning signage. This structural adjustment ensures that the point of physical recognition always precedes the $37m$ physical threshold, guaranteeing robust, uniform compliance.

5. PRACTICAL GUIDELINES FOR SIGN SPACING

○ Sensitivity for conservative design

Because both reaction time and achievable deceleration vary across drivers and conditions, it is useful to evaluate $d_{\text{min.}}$ across a range of plausible values (AASHTO, 2018; Mannering and Washburn, 2020). Wide tables are shown in full-width format (**Table 2.** and **Table 3.**).

Table 2. Minimum distance ($d_{\text{min.}}$) from $60km/h$ to $50km/h$.

Reaction time $t_r(s)$	Deceleration magnitude $a(m/s^2)$		
	1.5	**2.5**	**3.5**
0.7	40.0	28.6	23.8
1.2	48.3	37.0	32.1
1.5	53.3	42.0	37.1
2.0	61.6	50.3	45.5

When transitioning from theoretical kinematics to practical traffic engineering, a single deterministic value for minimum compliance distance ($d_{\text{min.}}$) rarely accounts for the full spectrum of human and environmental variability. A driver does not operate with uniform neuro-optical processing speeds, nor do vehicles interact with the pavement texture under identical frictional states. To establish robust traffic engineering standards, sensitivity testing across matrix od operational parameters is essential.

Table 2. illustrates this parametric sensitivity for a standard speed transition from $60km/h(16.67m/s)$ to $50km/h(13.89m/s)$. Analysing the data array in Table 2., it is demonstrated the non-linear interplay between physiological human latencies and physical braking limits:

- The best-case scenario ($t_r = 0.7s$ and $a = 3.5m/s^2$): An alert, highly responsive driver executing firm, aggressive deceleration requires a spital window of just $23.8m$. In this scenario, the reaction distance component consumes only $11.67m$ ($d_r = 16.67 \cdot 0.7 = 11.67m$), while the braking distance run takes $12.13m$ ($d_c = (16.67^2 - 13.89^2)/(2 \cdot 3.5) = 12.13m$).
- The nominal operational baseline ($t_r = 1.2s$ and $a = 2.5m/s^2$): Under typical urban driving conditions, an average driver experiencing a standard $1.2s$ reaction latency and applying a moderate, comfortable braking force of $2.5m/s^2$ requires a minimum distance of $37m$ ($20m$ for reaction and $17m$ for deceleration).
- The high-risked/ distracted scenario ($t_r = 2.0s$ and $a = 1.5m/s^2$): When cognitive load, age, fatigue or digital distractions lengthen reaction time to $2.0s$ and adverse weather or worn tires reduce comfortable braking to $1.5m/s^2$, the spital requirements surges to $61.6m$. Here, reaction distance alone expands to $33.34m$, accounting for more than half of the total physical envelope (Greenlee et al., 2018; Fambro et al., 1997).

Mathematically, increasing reaction time by $1.3s$ (from $0.7s$ to $2.0s$) shifts $d_{\text{min.}}$ upward linearly by $21.67m$ regardless of the deceleration rate. Conversely, decreasing deceleration from $3.5m/s^2$ to $1.5m/s^2$ expands the required distance hyperbolic-wise, adding an extra $16.2m$ to the braking distance (d_c). This demonstrates that under compromised road friction or conservative driving behaviour, physical space requirements expand rapidly, necessitating generous safety margins in both roadway and traffic engineering.

○ Legibility check and advance sign placement

The legibility distance must be checked because the driver cannot begin reacting before the sign is readable. **Table 3.** provides example legibility distances computed using (1) for typical numeral heights and several threshold angles (Dewar and Olson, 2007; Zwahlen and Schnell, 1999). These values should be interpreted as illustrative. Real-world visibility is affected by contrast, retro reflectivity, and environmental conditions.

Table 3. Example legibility distance $(d_{\text{leg.}})$ – relation (1).

Numeral high $h(mm)$	Minimum visual angle $\alpha(°)$		
	5	**10**	**16**
50	34	17	11
75	52	26	16
100	69	34	21
150	103	52	32
200	138	69	43
250	172	86	54

A kinematic calculation alone is insufficient to guarantee zone compliance. Physical braking can not begin until the human operator begin until the human operator visually registers and deciphers the traffic control device. Table 3. Quantifies this visual legibility distance $(d_{\text{leg.}})$ across standard numeral heights ($h \in \{50,75,100,150,200,250\}mm$) and three threshold visual angles ($\alpha \in \{5°, 10°, 16°\}$), derived using the trigonometric relation (1).

By contrasting the physical kinematic demands ($d_{\text{min.}}$) from Table 2. With the optical legibility bounds $(d_{\text{leg.}})$ from Table 3., traffic engineers can evaluate whether standard boundary placement is structurally safe or inherently defective. According to the previous discussion, related to the different types of observers, which referred to Figure 2., the following is an overview of the appropriate legibility distance $(d_{\text{leg.}})$, which any of the exact observers would be able to maintain safety and controlled.

1. **Optimal conditions ($\alpha = 5°$)**
   Under crisp daylight with clear visual acuity, even a small $100mm$ character provides $69m$ of legibility distance. This easily encapsulates the nominal $37m$ kinematic requirement as well as the extreme $61.6m$ delayed-reaction scenario. At $h = 250mm$, legibility reaches $172m$, granting driver a massive optical head-start.
2. **Standard environmental conditions ($\alpha = 10°$)**
   In typical dusk, nighttime or rainy conditions where contrast drops, a $100mm$ character yields only $34m$ of legibility distance. Because $34m < 37m$ $(d_{\text{leg.}} < d_{\text{min.}})$, placing a sign with $100mm$ text right at the speed zone boundary creates a physical safety deficit of $3m$. A driver will cross into $50km/h$ zone before the deceleration can be physically completed. To restore safety using character height alone under $\alpha = 10°$, character size must be scaled up to at least $150mm$, at $d_{\text{leg.}} = 52m$ (Federal Highway Administration, 2023).
3. **Adverse/ Impaired conditions ($\alpha = 16°$)**
   In heavy fog, high glare or for a driver with reduced visual acuity, the optical threshold collapses dramatically. Smaller numeral sizes ($50mm$ to $100mm$) yield legibility distances of merely $11m$ to $21m$. Even a substantial $150mm$ character offers only $32m$ legibility, which fails to meet the nominal $37m$ stopping requirement. Under these adverse conditions, only sizes of $200mm$, with $d_{\text{leg.}} = 43m$ or

$250mm$, with $d_{\text{leg.}} = 54m$ can clear the baseline $37m$ threshold. Furthermore, if an impaired visual angle, $\alpha = 16°$, coincides with a delayed reaction time ($t_r = 2.0s$ and $a = 1.5m/s^2$ implicates $d_{\text{min.}} = 61.6m$). Even the largest standard $250mm$ sign character, at $d_{\text{leg.}} = 54m$, fails to provide adequate distance for boundary-line placement.

If the expected $d_{\text{leg.}}$ is smaller than the required $d_{\text{min.}}$, i.e. when $d_{\text{leg.}} < d_{\text{min.}}$, for traffic engineers there are two straightforward mitigation options, that exist (Federal Highway Administration, 2023; Pline, 2001):

1. Upscaling character dimensions (h): Increasing letter and numeral height shifts $d_{\text{leg.}}$ upward linearly, extending visual detection range without altering sign placement position, i.e. increasing the legibility (larger numerals, improved contrast/retro reflectivity, better placement);
2. Advance sign placement: When sign dimensions are constrained by physical standards or budget limits, an advance warning **"Speed Limit Ahead"** must be positioned upstream at distance: $x = d_{\text{min.}} - d_{\text{leg.}}$. Adding a safety buffer, $d_b \approx (10 \div 20)m$, ensures driver recognition occurs well before the physical point of required braking, guaranteeing uniform compliance and maximizing both road safety and traffic control in each of the traffic scenario that follows.

○ Recommended buffers

A buffer distance (d_b) is recommended when the objective is robust road safety rather than minimal compliance. A practical buffer can represent variability in reaction time (e.g.,$+0.3s$), reduced braking capability in wet conditions, or conservative driver behaviour (gentler braking). When detailed local data are unavailable, a simple approach is to add $(10 \div 20)m$ to the computed $d_{\text{min.}}$ for urban approaches, and more for higher approach speeds. The exact value should be adapted to local standards and road environment.

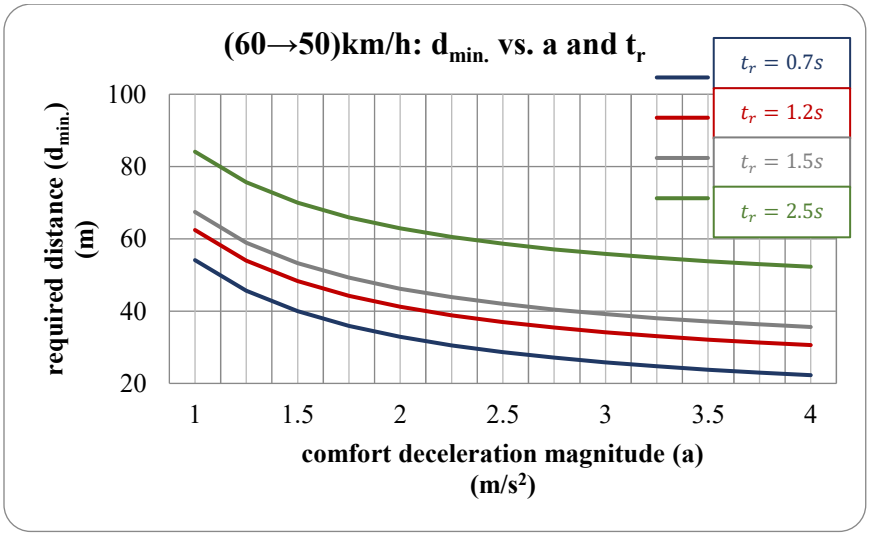


Figure 4. Sensitivity of $d_{\text{min.}}$ to reaction time and deceleration magnitude.

The parametric relationships governing the total required distance (from $d_{\text{min.}}$ to $d_{\text{req.}}$) for a $60km/h$ $(16.67m/s)$ to $50km/h$ $(13.89m/s)$ transition are plotted in Figure 4. Namely, the graph displays $d_{\text{min.}}$ as a function of the comfort deceleration magnitude $(a \in [1.0 \div 4.0]m/s^2)$ across the distinct reaction time parameters (t_r), offering crucial empirical insight into system sensitivity. Note that the legend in Figure 4. lists multiple parameter sets, capturing variation in reaction times (from alert driver with $t_r = 0.7s$, a nominal driver at $t_r = 1.2s$, up to delayed or distracted scenarios represented by higher curve with expanded reaction windows and offsets, with $t_r = 2.5s$).

While the baseline kinematic analysis establishes a theoretical minimum compliance distance $(d_{\text{min.}} \approx 37m)$ under ideal operational assumptions ($t_r = 1.2s$ and $a = 2.5m/s^2$), actual traffic environments are inherently stochastic, as it was presented in the paper before by analysing both reaction time and reaction distance. Human reaction latency, atmospheric visibility, pavement surface conditions and vehicle mechanical states fluctuate continuously. Designing infrastructure strictly for boundary-line compliance assumes a homogenous driver population operating under nominal conditions, a dangerous assumption in traffic safety engineering.

To achieve robust, high-confidence compliance rather than minimal, high-risk compliance, a design buffer distance (d_b) must be integrated into the total required spacing $(d_{\text{req.}})$, a relation followed form (8), as:

$$d_{\text{req.}} = d_{\min.} + d_b = d_r + d_c + d_b \tag{9}$$

The underlying family of curves in Figure 4. Is mathematically expressed by combining the linear reaction distance and inverse-linear braking distance equations:

$$d_{\min.}(a, t_r) = v_1 \cdot t_r + \frac{v_1^2 - v_2^2}{2a} \tag{9}$$

Substituting the fixed speed parameters: $v_1 = 60km/h = 16.67m/s$ and $v_2 = 50km/h = 13.89m/s$ yields:

$$d_{\min.}(a, t_r) = 16.67 \cdot t_r + \frac{16.67^2 - 13.89^2}{2a} = 16.67 \cdot t_r + \frac{277.89 - 192.93}{2a} = 16.67 \cdot t_r + \frac{42.48}{2a} \tag{10}$$

This formulation reveals the exact mathematical nature of the curves:

- **Vertical translation (Linear t_r offset)**
  Changing the perception-reaction time (t_r) shifts the curve along the vertical axis by $16.67m$ per second of reaction latency. For an alert driver $(t_r = 0.7s)$, the baseline offset is $11.67m$. For standard driver $(t_r = 1.2s)$, it shifts upward to $20m$. For delayed or distracted driver $(t_r > 1.2s)$, this linear offset raises the entire curve significantly.
- **Hyperbolic decay (Deceleration a sensitivity)**
  The term $42.48/a$ dictates the non-linear, but hyperbolic curvature. As deceleration (a) increases, $d_{\min.}$ decreases along a hyperbola. However, because the derivate $\partial d_{\min.}/\partial a = -42.48/a^2$ depends heavily on a, the marginal benefit of higher braking intensity drops off sharply.

A detailed examination of regions within Figure 4. provides vital insights for real-world traffic management and infrastructure design. Undoubtedly, the graph on Figure 4., can be decomposed into two, each important in its own way, regions both from its mathematical and physical meaning and real-world implication.

1. **The steep asymptotic region $(a < 1.5m/s^2)$**
   At low deceleration magnitudes $(a < 1.5m/s^2)$, representing very gentle, low-friction or icy road conditions, the slope $-42.48/a^2$, is extremely steep. At $a = 1.0m/s^2$, a driver with $t_r = 1.2s$, requires $d_{\min.} \approx 62.5m$. If the deceleration rate drops slightly further to $a = 0.8m/s^2$ due to a wet pavement or worn tire treads, $d_{\min.}$ surges past $73m$.
   Engineering implication: In regions subject to frequent adverse weather (e.g., snow, ice or heavy rain) or no steep downhill approach grades, traffic engineers cannot rely on nominal substantial safety buffers $(d_b \geq 20m$ to $30m)$ to prevent drivers from overshooting speed zone boundaries into high-risk collisions.
2. **The region of diminishing returns $(a > 2.5m/s^2)$**
   Conversely, as deceleration increases beyond $2.5m/s^2$, the curves flatten out. At $a = 2.5m/s^2$, and $t_r = 1.2s$, $d_{\min.}$ sits at $37m$. Doubling the deceleration force to a harsh $4.0m/s^2$ reduces $d_{\min.}$ to $30.6m$, a gain of only $6.4m$.
   Engineering implication: Pushing drivers to brake harder does not efficiently solve sign placement shortfalls. Severe braking causes passenger discomfort, increases rear-end collision risk from trailing vehicles and destabilizes heavy commercial trucks. Because physical braking gains plateau rapidly above $2.5m/s^2$, traffic engineers must solve placement deficits through advance signage and proper buffer allocation rather than expecting drivers to perform aggressive braking manoeuvres.

Figure 4. highlights that, reaction time (t_r) acts as a rigid, unyielding lower floor for $d_{\min.}$. Even under infinite acceleration $(a \to \infty)$, $d_{\min.}$ cannot drop below the vertical asymptote defined by $d_r = 16.67 \cdot t_r$. A time of $0.5s$ increase adds $8.33m$ in reaction time to the required spacing, regardless of how hard the driver brakes. In modern traffic environment distraction (e.g., smartphone usage or complex in-vehicle displays), high-percentile reaction delays $(t_r \geq 1.5s$ to $1.8s)$ are increasingly common. The upper curves of Figure 4. Explicitly capture these vulnerable driver states. So, by bridging theory and physical installation, engineers must apply standardized rules

of thumb derived from the parametric sensitivity in Figure 4., so the drivers can deal on with any unforeseen traffic situation, managing the vehicle safe and controlled.

Table 4. Recommended buffers in terms of real-world application.

Operational environment	Prevailing conditions	Recommended buffer (d_b)	Total spacing ($d_{\text{req.}}$)
Urban (nominal) approach	Daylight, dry pavement, low complexity	+10m	47.0m
Suburban/ Transition zone	Variable speed limits, moderate clutter	+15m to +20m	52.0m – 57.0m
Adverse environment	Frequent wet, icy pavement, night glare	+25m to +30m	62.0m – 67.0m
High perception load	Intersection, heavy commercial traffic	+30m+ (advance signage)	>67.0m

When field conditions restrict the legibility distance $(d_{\text{leg.}})$ below the required design spacing $(d_{\text{req.}})$, moving the primary regulatory sign or installing an upstream advance warning, **"Speed Reduction Ahead"**, is mathematically required. Incorporating these buffers distances transforms the step-by-step algorithm from a simple theoretical exercise into an adaptable design tool for real-world road safety and traffic control.

6. DISCUSSION

The proposed model is intentionally simple. Its value lies in connecting a common traffic-engineering decision (where to place a speed sign) to two measurable quantities: reaction time and longitudinal acceleration (Naumovski and Koltovska Nechoska, 2025). However, several limitations should be noted. First, braking is not perfectly constant. Real deceleration varies with brake application, road gradient, and anti-lock braking behaviour. Second, reaction time is context-dependent and can increase substantially under distraction. Third, sign recognition is not guaranteed: a driver may look away, a truck may temporarily block the sign, or the sign may be visually cluttered by other information. Despite these limitations, the model supports an important qualitative conclusion: small reductions in available distance can translate into meaningful non-compliance at the zone entry. Therefore, sign placement should be evaluated not only against regulatory rules, but also against the physical feasibility of compliance under realistic conditions. Where feasibility is marginal, advance signs or gradual speed-transition measures (e.g., multiple step-down limits) can improve both compliance and safety.

- First, longitudinal braking profiles in practice are non-linear. Real vehicle deceleration varies dynamically across the braking manoeuvre due to hydraulic system build-up delays (jerk limits), road gradient variations (AASHTO, 2018), pavement macrotexture conditions (Garber and Hoel, 2019), and anti-lock braking system (ABS) intervention. Downhill road grades, for instance, noticeably attenuate net braking efficiency, requiring an expanded physical stopping envelope (d_c) to achieve the same speed reduction.
- Second, human reaction time (t_r) is highly context-dependent and subject to stochastic distribution across driver populations (Olson, 1972; Fambro et al., 1998). Latencies increase substantially under cognitive distractions, driver fatigue, advanced age, or complex multi-lane driving environments where visual search times are prolonged (Greenlee et al., 2018; Urquhart and Young, 2021).
- Third, visual recognition is not guaranteed at the theoretical legibility boundary. Temporary physical sightline obstructions, such as high-profile heavy commercial vehicles in adjacent lanes or intense visual clutter from commercial signage and signalization can introduce detection delays that compress the effective legibility envelope $(d_{\text{leg.}})$ (Zwahlen and Schnell, 1999; Urquhart and Young, 2021).

Despite these operational simplifications, the model supports a critical qualitative conclusion: minor spatial shortfalls in available road distance translate into disproportionately severe non-compliance and elevated speed dispersion at zone boundaries. When available recognition distance falls below $d_{\text{min.}}$, driver cannot physically reach target speed (v_2) without executing aggressive, high-jerk braking manoeuvres that dramatically increase rear-end collision risks (Evans, 2004; World Health Organization, 2023).

Consequently, sign placement must be verified not merely against static regulatory guidelines (Federal Highway Administration, 2023; Pline, 2001), but against the physical feasibility of compliance under realistic, worst-case driver and environmental conditions. Where feasibility is marginal, traffic engineers should implement advance warning signage,

upscale numeral glyph heights, or deploy multi-stage speed transitions (e.g., stepping down from $80km/h$ to $60km/h$ to $50km/h$) to guarantee smooth, high-compliance speed harmonization.

7. CONCLUSION

A kinematic model was used to define a minimum distance for speed-limit compliance after a driver recognizes a sign (Naumovski and Koltovska Nechoska, 2025). The model separates the process into reaction distance and speed-change distance, leading to $d_{\min.}$ is equal to: $d_r = v_1 \cdot t_r$ – reaction distance and $d_c = (v_1^2 - v_2^2)/(2a)$, for deceleration. For a transition from $60km/h$ to $50km/h$ with $t_r = 1.2s$ and $a = 2.5m/s^2$, the resulting requirement is approximately ($\approx 37.0m$). The practical implication for road safety and traffic control is that sign placement should be verified against reaction time, braking capability, and sign legibility (Dewar and Olson, 2007; Fambro et al., 1997), and where necessary supported by advance warning and safety buffers (AASHTO, 2018; Federal Highway Administration, 2023).

Building upon this foundational kinematics, this framework offers municipal planners, highway authorities, and smart-city engineers a game-changing, cost-effective tool for proactive risk management. Traditional traffic control design has historically relied on static regulatory rules that treat human physiology and environmental variations as afterthoughts (Pline, 2001; Garber and Hoel, 2019). By directly linking optical legibility thresholds to real-world vehicle stopping dynamics, this methodology eliminates guesswork from infrastructure planning. Implementing this step-by-step design check enables road authorities to systematically identify high-risk speed transition zones before fatal crashes occur, protecting both vulnerable road users and infrastructure investments.

Moreover, in an era dominated by smart mobility, automated enforcement, and intelligent transportation systems (ITS) (Hancock and Parasuraman, 1992; Mannering and Washburn, 2020), infrastructure design must keep pace with modern driving realities. Misplaced speed signage does not merely reduce compliance; it invites abrupt emergency braking, increases rear-end collision risks, creates artificial traffic bottlenecks, and fuels driver frustration. By incorporating scientifically backed safety buffers and dynamic advance signage placement, road managers can dramatically elevate zone compliance rates while maintaining optimal traffic flow. Bridging human factor science with practical highway engineering delivers a scalable, high-ROI blueprint for building safer, smarter, and significantly more efficient roadway networks.

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