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Defining Maximum Traffic Flow Levels for Pedestrians and Vehicles in Shared Space

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ABSTRACT: Shared spaces are intended to accommodate pedestrians, cyclists and motorists on equal terms, yet practitioners still lack an *operational* tool for translating pedestrian–vehicle interactions into clear capacity limits. This study closes that gap by proposing a density-based delay model that expresses instantaneous vehicle speed as a function of local pedestrian concentration. The four free parameters of the model are calibrated with a genetic algorithm against a bank of pedestrian-vehicle scenarios generated in *PTV VISSIM*, allowing the analytical formulation to emulate the full microsimulation surface. Once calibrated, the model collapses rich interaction dynamics into an '-curve'—an envelope of pedestrian- and vehicle-flow pairs that preserves an acceptable average delay. The workflow is demonstrated on a Prague retail parking lot and shown to reproduce the observed balance between comfort, safety and throughput. By turning hours of simulation into a single design-ready curve, the framework offers planners a lightweight, reproducible means to size or retrofit low-speed shared zones and provides a foundation for further empirical and methodological extensions.

KEYWORDS: Pedestrian Safety; Shared Space; Traffic Flow; Traffic Modeling

1. INTRODUCTION

The primary motivation for this research is the pivotal role pedestrians play in the effective design and operation of shared spaces. In such environments, pedestrians are not merely one group of users but play a key role in shaping traffic dynamics, safety, and overall functionality. Pedestrian flow, safety, and interaction patterns are crucial to maintaining the usability of these environments, where informal negotiation between users replaces conventional traffic control. The objective of this study is to examine the relationship between pedestrian and vehicle flows in shared spaces and to identify combinations of flow intensities that allow pedestrian movement to be prioritized without disproportionately constraining vehicular traffic. Striking this balance is essential for preserving the effic iency and safety of the space, allowing for fluid, multimodal transport interactions under varying demand levels. This approach reflects the need to accommodate all participants in an equitable way, aligning with the broader objectives of shared space theory and urban mobility frameworks.

The concept of shared space represents a transformative approach in urban design, challenging traditional road layouts by fostering an environment in which pedestrians, cyclists, vehicles, and individuals with disabilities coexist with minimal segregation. Instead of relying on formal traffic regulations, these environments emphasize social interaction, visual communication, and shared responsibility among users. As defined by Hamilton-Baillie (2008), Karndacharuk et al. (2013), and Tzouras et al. (2021) shared space is designed to improve movement and comfort for all users, encouraging mutual respect and cautious behaviour without explicit modal prioritization.

Despite increasing interest in shared space implementation, practical questions related to operational performance and capacity remain insufficiently addressed. In particular, there is a need for transparent and reproducible methods that relate pedestrian flow to vehicle delay in a form suitable for capacity assessment. To address this challenge, this study develops a mathematical model capturing vehicle delay as a function of pedestrian density. The model is calibrated using microsimulation and validated through a real-world case study. By integrating analytical modeling with simulation-based optimization, the proposed approach provides a structured and replicable framework for assessing capacity constraints in shared space environments, offering practical guidance for urban mobility planning.

1.1 Literature review

Significantly, Tzouras et al. (2023) underscores the impact of shared spaces in urban settings, where their implementation has been linked to increased pedestrian crossings and reduced traffic speeds, indicating a shift towards more uniform driving behavior and potentially safer and more pedestrian-friendly environments.

Empirical studies further elucidate the dynamics within shared spaces, highlighting the nuanced interactions among road users. For instance, findings from Batista and Friedrich (2022) reveal that cyclists and pedestrians, in efforts to avoid traffic conflicts, may navigate towards the edges of the movement zone or seek safety in designated safe zones, underscoring the variability and unpredictability of pedestrian movement within these environments.

Furthermore, research from Singapore and Korea (Che et al. 2021) focuses on the behaviors of pedestrians and cyclists on shared sidewalks, suggesting that perceived control and priority significantly influence their interactions. This leads to cyclists exhibiting greater caution around pedestrians, who may conversely underestimate the risks posed by cyclists.

Kaparias and Wang (2020) concluded that shared space streets enhance pedestrian experience by higher level of

service and without causing noticeable delays in motorized traffic flow.

Moreover, the approach advocated by a comprehensive analysis by researchers from Italy and Germany (Orsini et al. 2023) on the effects before and after implementation of shared spaces provides compelling evidence of their potential to significantly reduce accident risks, thereby reaffirming the transformative capacity of shared spaces to create safer and more inclusive urban environments.

It seems that the overall performance of a transport system is based on the willingness of road users to share, which cannot be estimated using classic transport modeling approaches and policy assessment tools. Agent-based models (ABMs) are a possible solution to this problem; they use the metaphor of an autonomous agent, who acts on its own meaning that it is capable of making decisions considering the environment in which it operates, as well as the complex interactions with other agents. One of the main disadvantages of the already developed ABMs is that they require a deep knowledge of microscopic simulation tools and programming methods, so that planners can fully understand how these models work. A well-defined concept model can bridge the gap between theory and practice. That is what the Bazzan and Klügl (2014) researchers described in their study.

A study by Uttley et al. (2020) carried out observations of 66 pedestrian-driver and 124 driver-driver interactions in a shared space setting. In general, the results showed that pedestrians' failure to look towards a driver created the greatest uncertainty in the interaction, with the driver slowing down, but not completely stopping, in response to pedestrians. Looking towards the driver also influenced which road user took priority in driver-driver interactions. Groups of pedestrians were more likely to be given priority than an individual pedestrian, and the use of vehicle-based signals were also associated with taking priority during an interaction.

The integration of pedestrian crossings into urban road networks has been a subject of extensive global research, revealing a complex interplay between pedestrian movement, vehicular flow, and urban planning. A study (Methorst et al. 2007) conducted a comparative analysis between shared spaces and traditional road environments. This research highlighted that, unlike conventional settings with concentrated crosswalks, pedestrian crossings in shared spaces are distributed across multiple points, potentially enhancing road capacity by dispersing pedestrian flow.

The researchers (Forde and Daniel 2021) present an article on an innovative methodology for evaluating the safety of shared space implementations, as demonstrated through a case study in Italy. This methodology employs a novel surrogate safety measure, "time to avoided collision point" (TTAC), to identify traffic conflicts and to model the probabilistic relationship between these conflicts and crashes, utilizing the Lomax distribution. The study reveals a significant 53 % reduction in crash risk following the implementation of shared space, corroborating changes in user speed and spatial behavior.

Chaudhari et al. (2021) analyzed pedestrian safety under mixed traffic conditions in India and identified significant disparities resulting from the prioritization of vehicular traffic. Their findings, based on quantitative data on crossing times, accident rates, and compliance with pedestrian right-of-way, indicate a systemic imbalance that compromises pedestrian safety and underscores the need for context-sensitive design interventions.

The study presents (Johora and Müller 2020) a game-theoretic model to simulate interactions between pedestrians and vehicles in shared spaces, utilizing a Stackelberg game approach to predict the behavior of road users. Key factors such as speed, proximity, and decision-making dynamics are integrated into the model through 22 behavioral parameters. Sensitivity analysis shows the model's potential to capture complex interaction patterns, though further calibration with real-world data is required. The results suggest that the model has promise to improve safety and efficiency in shared spaces by providing a structured framework to understand pedestrian-vehicle interactions.

Furthermore, Dostál et al. (2020) applied a fine-grained microsimulation framework that tracks speed variance, pedestrian delay, and conflict-point density in order to assess public spaces in Prague. Although their approach is methodologically rigorous, it represents a metric-driven evaluation that is more analytical in nature. Therefore, it is not fully aligned with the user-centred perspective adopted in the present study.

While these studies provide important insights into shared space design, none of them directly address the dynamic interplay between pedestrian flow and vehicle delay in a form that can be used for capacity estimation. Our study bridges this gap.Building upon this foundation, the present study proposes a novel modeling approach that combines analytical delay functions with simulation-based optimization to define capacity limits for shared spaces.

In the course of the literature review, several studies and research projects have examined the concept of shared spaces, particularly focusing on the absence of designated pedestrian crossings. The findings suggest that shared spaces without crosswalks tend to support higher traffic capacity, as the interaction between pedestrians and vehicles becomes more fluid and intuitive. Rather than relying on traffic controls or formal crossings, these spaces allow for natural negotiation of priority, with an emphasis on eye contact and yielding, effectively leading to a "first-come, first-serve" dynamic. This interaction-based approach can improve the overall functionality of shared spaces while reducing unnecessary delays caused by stop-and-go traffic behavior at traditional crossings.

1.2 Research gap and goals of the paper

While previous studies provide valuable insights into shared space design, few quantify the dynamic interplay between pedestrian and vehicle flows in a manner suitable for capacity estimation. The goal of this study is to develop a modeling framework that captures these interactions and defines operational capacity limits for shared spaces.

To achieve this, the study combines analytical delay functions with simulation-based optimization. Matlab is used for data preparation and analysis, while PTV Vissim simulates pedestrian-vehicle interactions within a shared space. These simulations provide insights into how shared spaces can remain efficient and safe under varying levels of use, ensuring the environment serves both pedestrians and vehicles without excessive congestion or safety compromises.

The research also aims to derive practical guidelines for planners and policymakers, enabling them to assess whether a shared space design is appropriate under specific traffic conditions and to consider additional parameters such as public space layout and safety regulations. Importantly, the concluding sections present calculated thresholds for pedestrian and vehicle flow intensities that quantitatively characterize their mutual influence. These thresholds, derived directly from the analytical and simulation models, provide an evidence-based framework to assess the feasibility of shared space implementation under observed traffic conditions and to inform data-driven decisions on the suitability of shared space solutions.

Importantly, the concluding sections of this article present calculated thresholds for pedestrian and vehicle flow intensities that quantitatively characterize their mutual influence.

These thresholds are derived directly from the analytical and simulation models, providing an evidence-based framework to assess the feasibility of shared space implementation under observed traffic conditions. Consequently, future traffic surveys can be evaluated against these thresholds to inform data-driven decisions on the suitability of shared space solutions in specific contexts.

This derived flow curve delineates the operational boundary of acceptable flow levels for users of shared spaces. Given that there are currently no universally established standards for optimal pedestrian and vehicle intensities in shared environments, this study offers a methodological advancement by defining quantifiable limits grounded in rigorous modeling and empirical validation.

Expected contributions:

1. A worked demonstration on a real shared space, illustrating how the derived capacity envelope can guide planning decisions.
2. A general delay model linking pedestrian density to vehicle behaviour in shared spaces, allowing quantifiable assessment of operational limits.
3. An evidence-based framework for evaluating the feasibility of shared space implementation, supported by simulation and analytical modeling.

The paper is organized as follows. Section 2 summarizes the methods used and proposes a mathematical model that describes the interaction between vehicles and pedestrians. The algorithm for the solution is provided. Section 3 explains how simulations of pedestrian-vehicle interactions were created using Matlab and VISSIM, with optimization via a genetic algorithm. Section 4 describes a real-world shared space case study in Prague, detailing data collection and analysis of pedestrian-vehicle behavior. The model's predictions are compared with VISSIM results to assess the traffic flow and capacity of the shared space. The paper closes in Section 6 with a summary of the conclusions.

2. METHODS

This study focuses on defining the maximum thresholds for pedestrian and vehicle flow intensities that maintain the attractiveness of shared spaces for both user groups. To this end, a series of simulations was conducted using VISSIM and MATLAB to identify the optimal balance between pedestrian and vehicular movement. The framework of our contribution is following:

1. Based on several assumptions (see below this list), we propose the relation between vehicle flow actual acceleration and pedestrians crossing the road with tuneable scalar parameters a_i.
2. In order to tune the parameters a_i, we perform large number of random scenarios in VISSIM of interacting vehicles and pedestrians in the model of shared zone a compare travel times with results from proposed relation with help of Matlab.
3. Tuning of parameters a_i is managed automatically using optimization methods.

Within the framework of the following analysis of shared zones we introduce several assumptions:

- The flow of vehicles follows a dedicated corridor that has one-dimensional character, i.e., the location on the corridor is described by $x \in \langle 0, L \rangle$, where L is the length of the corridor.
- The main influence on vehicle flow have pedestrians crossing the corridor.
- There exists a relation between the influence of pedestrians at coordinate and the instant acceleration of the vehicle $a(x) = \dot{v}(x) = \frac{\partial v}{\partial t}(x) = v_{,t}$.

2.1 Modeling the interaction of vehicle flow and pedestrians

Pedestrian flow can be described by its density $\lambda(x)[ped.\ m^{-1}\,h^{-1}]$. We propose the relation between this density and vehicle instant acceleration in the form

$$
\begin{aligned}
(1) \qquad & \lambda(x) = 0 \wedge v_{min} < v(x) < v_{max} \Longrightarrow \\
& \dot{v}(x) = -a_1\,\lambda(x)\exp(-a_2\,\lambda(x)) - a_3\,\lambda'(x)\,, \\
& v(x) > v_{max} \vee v(x) < v_{min} \Longrightarrow \dot{v}(x) = 0\,, \\
& \lambda(x) = 0 \wedge v_{min} < v(x) < v_{max} \Longrightarrow \frac{\partial v(x)}{\partial x} = a_4,.
\end{aligned}
$$

where a_i are positive scalar parameters, $\lambda'(x)$ is the spatial derivative of the density of pedestrian flow, and v_{max} and v_{min} are the maximum and minimum allowed speed of vehicle flow, respectively. As it is further presented, the proposed model captures critical aspect of the interaction and drivers behavior.

The first condition is the most important one, as it describes the delay when pedestrians are present. Its form comes from these fundamental assumptions:

- The flow delay $\dot{v}(x)$ increases with increasing pedestrian flow $\lambda(x)$. This behavior is characterized by parameter a_1. However, if $\lambda(x)$ increases to higher values, the influence on $\dot{v}(x)$ decreases, as vehicles will force pedestrians to let them pass at least with the given speed v_{min}, no matter how many pedestrians are present. This phenomenon can be seen when the vehicle is going through an area of standing crowds - the parameter a_2 describes this behavior.
- The higher the pedestrian flow along the corridor (i.e. derivative $\lambda'(x)$ increases), the higher is the delay. The rate of this change describes the parameter a_3.

Although the presented model should offer sufficiently accurate description of the flow-pedestrians interaction, it is not able to capture these types of situation:

- Abrupt decrease of $\lambda(x)$ to the value of 0.
- Keeping the minimal speed v_{min}, even the model falsely indicates delay.
- Accelerating to the maximum speed v_{max}, when there are no pedestrians and staying at this speed.

Few more restrictions are needed to be added:

1. The second condition of (1): This condition prescribes upper and lower limits of the flow actual speed,
2. The third condition of (1): In case there are no pedestrians present, the flow accelerates up to v_{max} this acceleration is described by the parameter a_4.

To be absolutely clear, find useful to outline physical meaning of the scalar parameters a_i;

a1 linearly scales the influence of density of pedestrian flow $\lambda(x)$,

a2 is damping coefficient which tries to capture the behavior when vehicle flow increases to its limits - at that point, vehicle flow moves slowly forward with constant speed, therefore, the acceleration must be attenuated,

a3 linearly scales the influence of density of pedestrian flow spatial rate $\lambda(x)$, which means, the the more are abrupt changes of $\lambda(x)$ in space, the stronger is the effect of vehicle flow acceleration or delay,

a4 represents vehicle flow spatial acceleration when the road is clear of the pedestrians and the flow has not reached v_{max} yet.

2.2 Transport equation

One investigates the shared space by employing proposed model (1) and transport equation

$$(2)\quad k_{,t} + q_{,x} = 0\,,$$

where $k(x)$ is vehicle density and $q(x)$ is the vehicle traffic flow. Subindex $_{,t}$ and $_{,x}$ refers to the temporal and spatial derivative, respectively. Taking into account the general relation $q(x) = k(x)v(x)$, where $v(x)$ is the vehicle speed at position x, we can rewrite the equation as

$$(3)\quad k_{,t} + k_{,x}v + k\,v_{,x} = 0\,.$$

In order to explicitly obtain $k(x, t)$, we have to provide two functions $v(x)$ and $v_{,x}(x)$, which can be derived from the proposed model (1). Combining fundamental relations

$$(4)\quad v = \frac{\mathrm{d}x}{\mathrm{d}t}\,,\qquad v(x + \mathrm{d}x) = v(x) + v_{,t}(x)\,\mathrm{d}t$$

we get to the expression

$$(5)\quad v(x)\,\frac{\mathrm{d}v}{\mathrm{d}x} = v_{,t}(x)\,.$$

Now, performing the integration

$$(6)\quad \int_{v_0}^{v(x)} v\,(x)\,\mathrm{d}v = \int_{x_0}^{x} v\,(x)_{,t}\,\mathrm{d}x\,,$$

we obtain the final expression for the first of the two sought functions

$$(7)\quad v(x) = \pm\sqrt{v_0^2 + 2\int_{x_0}^{x} v\,(x)_{,t}\,\mathrm{d}x}\,.$$

Now, it depends on the complexity of $\lambda(x)$, so the analytical solution of the integral in (7) can be found, since $v(x)_{,t} = f(\lambda(x))$, as proposed (1). Depending on that, one can perform analytically or numerically the derivative end express the second unknown function $v_{,x}(x)$.

2.2.1 Investigation of semi-analytical smooth solution of simple case

The best option to solve the partial differential equation in this case (3) is to use the central differences method in an implicit form, since the problem is not very complex and no dissipation will occur. The discretized transport equation has the form

$$(8)\quad \frac{k_i^{n+1} - k_i^n}{\Delta t} + \frac{k_{i+1}^{n+1} - k_{i-1}^{n+1}}{2\Delta x}\,v_i + k_i^{n+1}\,v_{i,x} = 0\,,$$

where n and i denote discrete temporal level and spatial coordinate, respectively. The corresponding system of linear equations is then iteratively solved using the Δt step. The initial conditions ($k_i^0 = 0$) and the boundary condition ($k_1^n = q_{in}/v_{in}$) are provided, where q_{in} is the input flow and v_{in} is the speed of vehicles coming from unaffected areas by pedestrians.

As a demonstration example, we show the problem of a segment of total length of $L = 100$ m with constant density of pedestrian flow $\lambda(x) = \bar{\lambda}$. Then

$$(9)\quad v(x) = \sqrt{v_0^2 + 2\int_{x_0}^{x}\left(-a_1\,\bar{\lambda}\exp(-a_2\,\bar{\lambda})\right)\mathrm{d}x} = \sqrt{v_{in}^2 - 2\,a_1\,\bar{\lambda}\exp(-a_2\,\bar{\lambda})\,x}\,,$$

$$v_{,x}(x) = -\frac{a_1\,\bar{\lambda}\exp(-a_2\,\bar{\lambda})}{v_{in}^2 - 2\,a_1\,\bar{\lambda}\exp(-a_2\,\bar{\lambda})\,x}$$

are analytical expressions for the speed and its spatial derivative. With these analytical relations, we can express v_i and $v_{i,x}$ in (8) and solve this PDE.

Namely, for $\bar{\lambda} = 10$, $[a_1, a_2] = [0.0559, 0.0259]$, we can see the plotted functions (see Figure 1). Note that till now everything was processed analytically using only the first equation of (1), which works only in simple cases, when $\lambda(x) \neq 0$ and has no/small gradient.

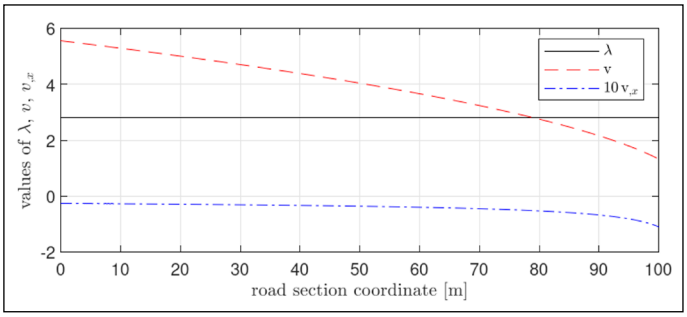
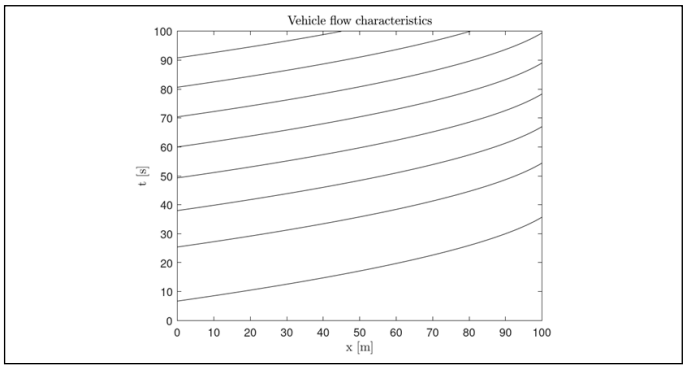
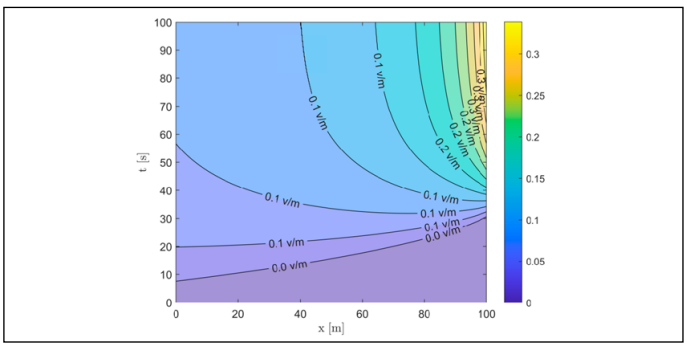


Figure 1: Example of distribution of the values the crucial quantities along the 100 m long road section

Now, we can proceed to the analysis of the segment by solving the PDE (8). From the results (see Figure 2) we can observe that the vehicle density increases both in time and space, which is expected behavior. At the end of the section ($x > 90$ m) the density is reaching critical value 0.3 v/m, which is maximum physically possible density, therefore, the model is within its limits in the sense of behavior description.



(a) Characteristics of the PDE (8)



(b) Vehicle density distribution in space-time diagram

Figure 2: Solution of the PDE (8) for input flow $q_{in}(t) = 0.5(1 - e^{-0.05t})$ and input speed $v_{in} = 5.56\ m\ s^{-1}$ at $x = 0$ m

2.2.2 Algorithm for fully numerical solution of general problem

In real problem, the density of pedestrian flow may have complex character which can not be described by smooth function. In that case, both functions $v(x)$ and $v_{,x}(x)$ are obtained numerically, i.e. by numerical integration of (7) and

then performing the discrete derivative of the vector $v(i)$ with respect to Δx. The vector $\lambda'(i)$ must also be obtained as a discrete derivative of given $\lambda(i)$. To be absolutely clear, we give the algorithm to the reader. The given quantities and constants are:

- section length L, time length of the simulation T,
- speed of incoming flow v_{in} and at the same time maximal allowed speed v_{max},
- minimal allowed speed v_{min},
- input flow $q = q(t)$,
- distribution of the density of pedestrian flow $\lambda(x)$.

Then the proposed algorithm is as follows:

Algorithm for solution of vehicle density $k(x;t)$

Step 1: Dicretize spatial and temporal coordinates with chosen Δx and Δt and prepare vector of values $\lambda(i)$ at nodes of discretized space.

Step 2: Compute $\lambda(i)_{,x}$ by discrete derivative of $\lambda(i)$.

Step 3: Compute $v(i)$ by means of

- numerical integration of (7) if $\lambda \neq 0$,
- $v_{i+1} = v_i + a_4\,\Delta x$ if $\lambda = 0$.

Step 4: For all $v_i > v_{max} \rightarrow v_i = v_{max}$.

Step 5: For all $v_i < v_{min} \rightarrow v_i = v_{min}$.

Step 6: Solve discretized PDE (10) fo every $t + \Delta t$ up to the time T

$$\frac{k_i^{n+1} - k_i^n}{\Delta t} + \frac{k_{i+1}^{n+1} - k_{i-1}^{n+1}}{2\Delta x} v_i + k_i^{n+1} \frac{v_{i+1} - v_{i-1}}{2\Delta x} = 0\,. \qquad (10)$$

where $k_i^0 = 0$ and $k_1^n = q(t)/v_{in}$, i.e, solve the system

$$A\,k^{n+1} = k^n, \qquad n = (0, 1 \ldots (T - \Delta t)\,/\,\Delta t), \qquad (11)$$

where A is the coefficient matrix (see Apendix A).

Note that all conditions of (1) are included.

3. OPTIMIZATION OF THE PROPOSED MODEL PARAMETERS - ARTIFICIAL ROAD SECTION

Although the model (1) should be able to capture crucial aspects of vehicle-pedestrian interaction, we still face the problem of estimation of its parameters $\mathbf{a} = [a_1, a_2, a_3, a_4]$. Ideal approach would be to find a real shared space with a rich variation of pedestrian density $\lambda(x)$, vehicle input flow q_{in} and vehicle incoming speed v_{in} and optimize the model according to the real data. We performed several traffic surveys in the field (one example is demonstrated in Sec.4) and realized, that all the quantities $\lambda(x)$, q_{in}, v_{in} have constant character, where values are given by the properties of the shared zone. Therefore, learning data for the governing model (1) would be very poor. Hence, we propose using the available software for simulation of vehicle flow and pedestrian crossing to create rich learning data. Although it can be tricky to model shared space in such software, we propose the approach, which seems to be working accurately enough. The subsequent approach is as follows:

STEP 1:
Generate large number of random scenarios with varying pedestrian and vehicle flow in VISSIM and use the results (travel times) as a learning data for numerical model (1).
STEP 2:
Compute given scenarios using the proposed numerical model (1) in Matlab and compare the results with VISSIM – optimize the model parameters a_i, e.g., with genetic algorithm, so the travel times match for both methods (VISSIM and Matlab).
STEP 3:
Finally, we can compare the prediction of tuned proposed model (1) with real in-field study of shared space, in order to outline the validation (see Sec. 4).

3.1 Vissim - generation of training data

In this chapter, we describe the process of modeling a shared-space scenario using the PTV VISSIM simulation tool. The model focused on analyzing the interaction between pedestrians and vehicles on a 100-meter stretch of a bidirectional roadway. This section was designed to replicate real-world shared spaces, where pedestrians and vehicles coexist and the prioritization of one over the other is not explicitly defined.

3.1.1 Model design

The roadway segment was modeled with a width of 6 meters, designed to accommodate unidirectional vehicle traffic. A series of 20 pedestrian crossings, each 5 meters wide, were placed perpendicularly across the road at regular intervals. At each j-th crossing, pedestrian flow q_j was defined as

$$(12)\quad q_j = \int_{x_j-2.5}^{x_j+2.5} \lambda\,(x)\,\mathrm{d}x\,,$$

where x_j is the location of the crosspoint of the vehicle corridor and of the center axis of the j-th pedestrian crossing and $\lambda(x)$ is given pedestrian density of flow. The crossings were crucial in understanding the interaction dynamics between pedestrians and vehicles, simulating a dense shared-space scenario. To accurately represent the operational constraints of shared spaces, both a maximum and input vehicular speed of 20 km/h was set. This speed is typical in such environments, where lower limits are enforced to reduce the risk of accidents and enhance the safety of vulnerable road users, such as pedestrians and cyclists. By applying this speed constraint, the model aimed to replicate realistic traffic behavior and assess how this would impact vehicle travel times in high pedestrian-flow areas.

3.1.2 Data Collection and Traffic Flow Analysis

At the beginning and the end of the 100-meter segment, detectors were placed to measure the time taken for each vehicle to traverse the road. This data was used to evaluate vehicle delays caused by interactions with pedestrians. The analysis revealed that 72 seconds was the maximum tolerable time for a vehicle to pass through this segment without significant disruption to overall traffic flow. This threshold was derived by analyzing various simulations, where increased pedestrian flow led to progressive delays in vehicle movement. The 72-second limit also ensures that the vehicle maintains a minimum speed of 5 km/h. This speed was selected because, below this threshold, the vehicle would be moving slower than a pedestrian, making vehicular movement increasingly inefficient and random. The 72-second limit was considered optimal to balance vehicle and pedestrian needs while maintaining efficient road use (see Figure 3).

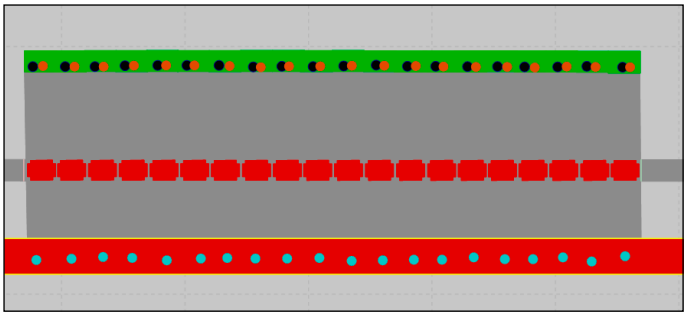


Figure 3: Model (2D) of shared space in VISSIM highlighting conflict uones at pedestrian-vehicle interaction points

3.1.3 Conflict Zones and Interaction Modeling

Conflict zones were established at each pedestrian crossing, where vehicles and pedestrians interacted. The model did not assign explicit priority to either road user, instead employing a "first-come, first-serve" rule. This rule mimics real-world shared spaces, where right-of-way is determined dynamically based on the timing of pedestrian and vehicle arrivals at crossing points. In the VISSIM simulation, this behavior was represented by the "set undetermined as status" setting, allowing for a more fluid and realistic interaction between different users of the space.This approach aimed to capture the organic and spontaneous nature of shared spaces, where road users negotiate their movements in real-time without rigid adherence to predefined traffic rules. Such interactions are essential to assess the functionality and safety of shared spaces, where conventional traffic controls are often minimal or absent (see Figure 4).

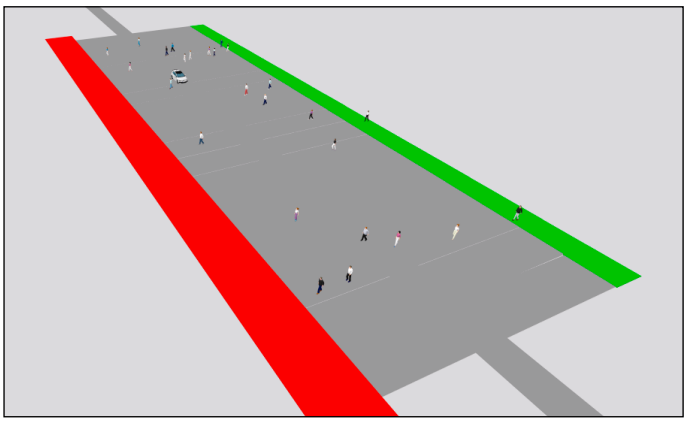


Figure 4: Microsimulation model of traffic and pedestrian interactions in a 100-meter shared space segment using Vissim

3.2 Optimization with genetic algorithm

Fitting of the proposed model (1) was performed using a genetic algorithm. The objective function (OF) was defined as

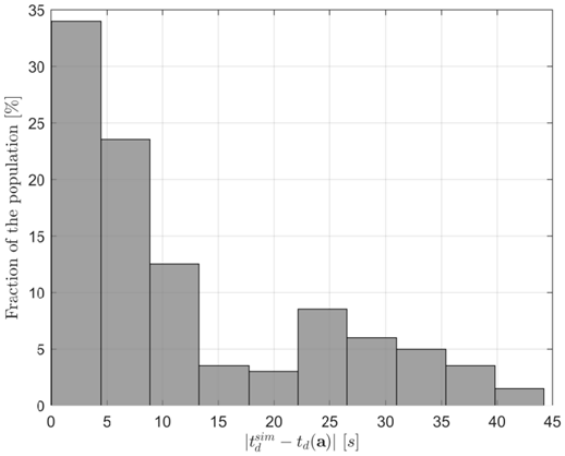
$$\epsilon = \sqrt{\sum_{i=1}^{n} \left(t_d^{sim} - t_d(a)\right)^2} \tag{13}$$

where n is the total number of scenarios and t_d^{sim} and t_d are the average time delays of the vehicles due to the presence of pedestrians obtained by Vissim simulation and by the proposed model (1), respectively. Optimal parameters $\mathbf{a}$ were searched to minimize the given OF. The settings of the genetic algorithm are summarized in the attached table (see Table 1).

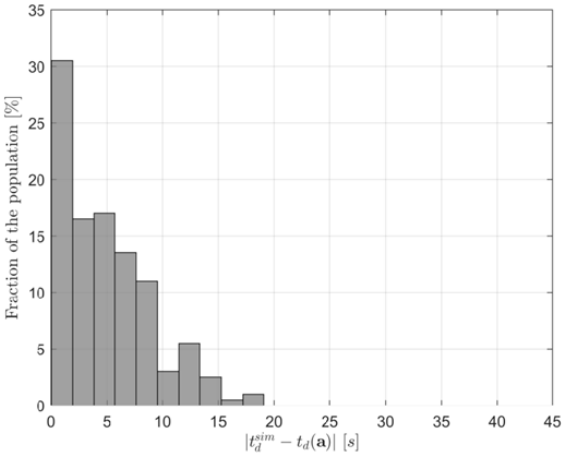
The situation before and after optimization is shown in the Figures 5.

Population size	Number of elite individuals	Number of children from crossover	and mutation
50	10	32	8

Table 1: Setting of the optimization



(a) Histogram of absolute error - the 1st generation



(b) Histogram of absolute error - the 346th generation

Figure 5: Optimization results

Optimal parameters of the proposed model (1), which solves the minimization of the OF (13) were obtained with the following values

$$a = \begin{bmatrix} 0.080031082931897, & 0.055611445941, \\ 0.165905674924467, & 1.068400545572201 \end{bmatrix}. \tag{14}$$

4. VERIFICATION ON THE MODEL REPRESENTING THE REAL SHARED ZONE

The proposed model (1) can now be together with obtained parameters (14) used for prediction of the capacity of the real given road section, where are freely moving pedestrians. As a demonstration, we take the real problem of straight road section, where pedestrians are frequently crossing on order to move between parking lot and the shopping center.

4.1 Traffic survey in the field - the setup

The verification was conducted on model of a real-world shared-space setting in the Czech Republic, specifically a parking lot in front of a commercial retail chain located in the northern part of Prague. This store has requested not to

be named in this article. This site, which currently operates as a de facto shared space, provided valuable insights into how pedestrian and vehicular flows could be harmonized. By modeling the flow of pedestrian movement and its effect on vehicle flow, the simulation helped identify thresholds at which pedestrian priority begins to significantly hinder vehicular traffic.

The parking lot was selected because it represents a typical shared-space scenario with frequent and uncontrolled pedestrian-vehicle interactions due to the absence of dedicated pedestrian crossings directly in front of the store. The site layout, including the 30-meter-long area in front of the main entrance and the arrangement of vehicle lanes and pedestrian access points, provides a representative geometry for studying shared-space dynamics and potential conflict points between users. This unique setting provided a relevant scenario to analyze the spontaneous negotiation of movement, characteristic of shared spaces, and to observe how pedestrian-vehicle conflicts naturally arise and are resolved. Understanding interactions and conflict patterns here allows insights to be applied to other urban environments with similar geometries and types of conflicts.

The survey, conducted in May 2024, specifically targeted peak hours on a Friday afternoon between 14:00 and 16:00, a time when pedestrian and vehicle activity was at its highest. The study focused on a 30-meter-long section directly in front of the store's main entrance, where pedestrian traffic was concentrated, and vehicles frequently passed through. This space, characterized by its significant volume of both pedestrians and vehicles, provided an ideal environment to study real-time interactions and behaviors in a semi-structured context.

Data collection was carried out using a camera mounted on a vehicle, capturing video footage of pedestrian-vehicle interactions over a two-hour period. The recorded footage was then analyzed using DataFromSky software, which enabled detailed tracking of all movements within the recorded area.

The analysis of these data enabled the extraction of critical information regarding the interaction dynamics in a shared space environment. The ability to calculate vehicle speeds and track exact paths for both vehicles and pedestrians was particularly important to understand how space was negotiated in the absence of formal traffic control mechanisms. And helped us to decide how to model shared space in Vissim, as was described in Section 3.1.3. In this uncontrolled setting, where right-of-way was established through spontaneous interactions, the study contributed to a deeper understanding of how shared spaces function under real-world conditions. The predicted thresholds for pedestrian and vehicle flows provide practical guidance for planners, indicating flow combinations where pedestrian priority begins to restrict vehicle movement. Such insights can inform redesigns or policy interventions to enhance safety and operational efficiency.

4.2 Theoretical analysis of the in field survey

The proposed tool may be used to estimate the capacity of a given shared space. For the term "capacity of the shared space", we propose the following definition:

Def. 1. *The shared space reaches its capacity when the average time delay hits the given critical value* t_d^{lim}.

In our case, the average speed of the incoming vehicles is 20 km/h. That means that unaffected flow pass through given 30 m long section in 5.4 seconds. We define that the maximum acceptable delay is $t_d^{lim} = 4\ s$, i.e., travel time $t_{tr} = 9.4\ s$. One can construct the set $\Omega \subset \boldsymbol{R}^2$ that contains pairs $[q_p, q_v] \in \Omega$ that do not cause the t_d^{lim} to exceed. This is done by means of Vissim and and then the results of proposed model (1) are given due to verification. Finally, we outline the validation with the real data.

4.2.1 Models setup

A second model was developed to closely reflect the real-world conditions observed in the parking lot in front of a shopping center, where a traffic survey was conducted. In the actual observed space, the roadway was bidirectional, with vehicles moving in both directions and pedestrians crossing from both sides. Since the real measured traffic flow was the same for both directions, pedestrian crossings influenced both directions equally and the directions do not affect each other, we are allowed to perform all simulations and analyses only for one direction, left to the right (see Figure 6, Figure 7).

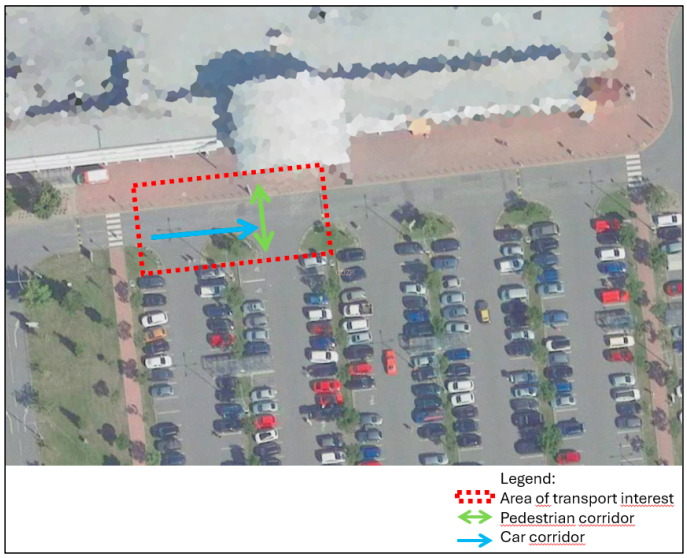


Figure 6: Map of the study area with pedestrian and vehicle corridors



Figure 7: Interaction between two pedestrians and an approaching vehicle from the left

Vissim It features a 6-meter-wide roadway segment, along with a 10-meter-long pedestrian section that intersects the road, accurately replicating the shared space where vehicles and pedestrians interact. A maximum vehicle speed of 20 km/h was set to simulate typical conditions, ensuring pedestrian safety and realistic traffic flow dynamics. The flow of vehicles and pedestrians is given by the values $\bar{q}_v$ and $\bar{q}_p$, respectively. The rule "first-come, first-serve" was associated with the crossing.

Proposed model (1) Both the maximum v_{max} and input v_{in} speed were set to 20 km/h. For minimal speed v_{min}, no limit was set. Instead of a constant input vehicle flow $q_v = \bar{q}_v$, a smooth increase in time was prescribed

(15) $q_v(t) = \bar{q}_v \exp(-0.5t)$,

in order to avoid artificial oscillation of density in the further solution of the PDE (8).

The pedestrian flow is described as

(16) $\lambda(x) = \frac{q_p}{l} h(x-20), \quad x \in (0, 30)$,

where q_p is input pedestrian flow in Vissim, h is the Heaviside step function and l = 10 m is the legnth of the pedestrian crossing.

4.2.2 Estimation of the capacity

Comparison between Vissim and proposed model is provided (see Figure 8 - Figure 11). At first, using Vissim, we searched for combinations of vehicle and pedestrian intensities $[q_p, q_v]$ at the boundary of the acceptable set Ω. The travel times are given (see red values in Figure 8). Then, computation with proposed model (1) with optimal parameters (14) was performed (see resulting blue travel times in Fig. 8). One can see that both travel times have similar decreasing trend and are comparable one to each other.

At the same time, the PDE for vehicle density (10) was solved and the solution was compared with the situation during the Vissim simulation (see Figure 9 - Figure 11). Considering that the maximum reachable density k is approximately $k \approx 0.15$ v/m, we can verify, that both Vissim and the proposed model indicate the formation of traffic congestion with increasing vehicle flow.

Finally, we can confirm that the real-world shared space (see Figure 6) is relatively far from reaching its capacity (see the green cross in Figure 8), which matches our observations (see Figure 7).

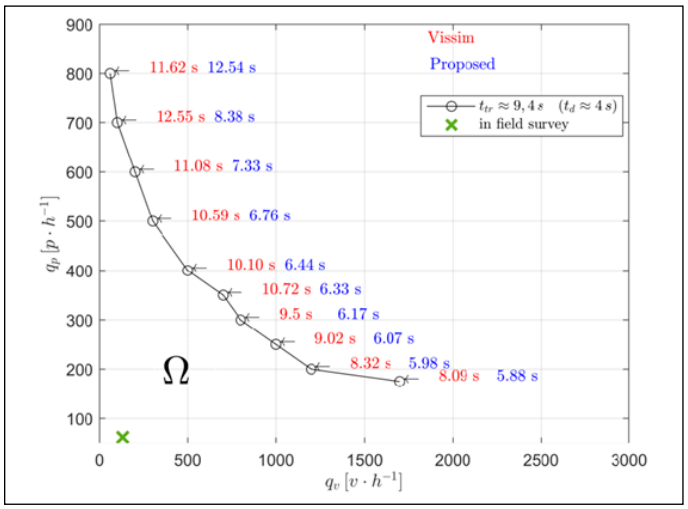
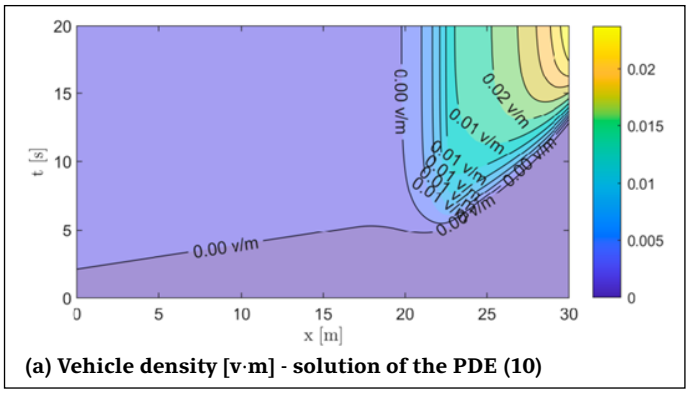
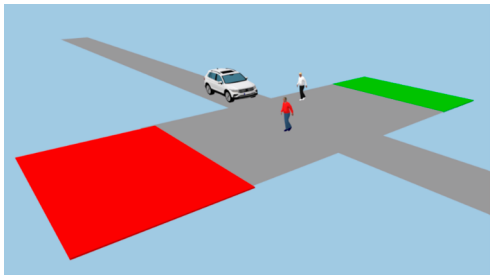


Figure 8: Estimation of the set Ω by VISSIM (red), representing the under-capacity status of the shared space and verification of Proposed model (blue)

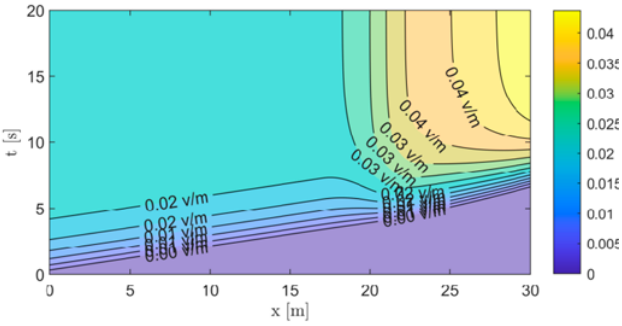


(a) Vehicle density [v·m] - solution of the PDE (10)

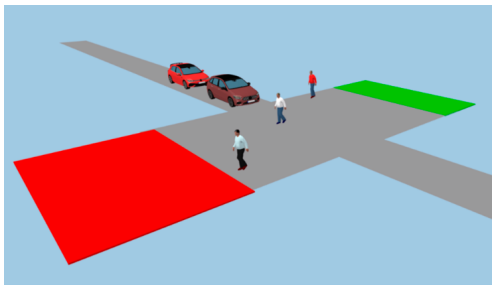


(b) Typical situation during Vissim simulation

Figure 9: Comparison of the situation for scenario no. 1: $[q_v = 60\ veh \cdot h^{-1}, q_p = 800\ ped \cdot h^{-1}]$

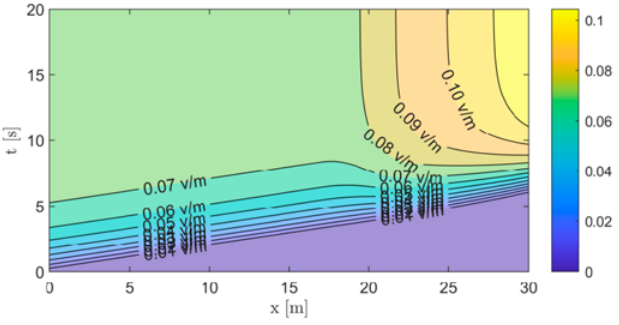


(a) Vehicle density [v·m] - solution of the PDE (10)

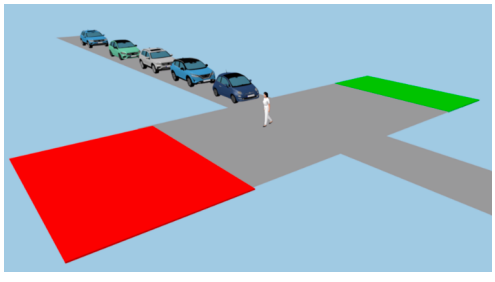


(b) Typical situation during Vissim simulation

Figure 10: Comparison of the situation for scenario no. 4: $[q_v = 500\ veh \cdot h^{-1}, q_p = 400\ ped \cdot h^{-1}]$



(a) Vehicle density [v·m] - solution of the PDE (10)



(b) Typical situation during Vissim simulation

Figure 11: Comparison of the situation for scenario no. 9: $[q_v = 1200\ veh \cdot h^{-1}, q_p = 200\ ped \cdot h^{-1}]$

5. DISCUSSION

This study contributes to the growing body of literature on shared space by presenting a new modeling approach that quantifies pedestrian-vehicle interactions using delay functions calibrated through microsimulation. The findings clearly show that pedestrian density significantly affects vehicle behavior, especially in delay and yielding patterns. This aligns with the conceptual principles of shared space (Hamilton-Baillie 2008), reinforcing the notion that increased pedestrian presence encourages safer, slower vehicle movement. However, our results also highlight capacity constraints that have not been explicitly quantified in earlier research Kaparias and Wang (2020) or Tzouras et al. (2021), thus extending current understanding by providing measurable thresholds for coexistence.

In comparison with prior studies, such as Kaparias and Wang (2020) and Tzouras et al. (2021), which mainly focused on qualitative behavioral descriptions and general performance assessments of shared spaces, our work introduces a quantitative, operational tool that estimates capacity limits. This integration of analytical modeling and microsimulation addresses a key gap in the literature where practical, data-driven models for shared space evaluation are scarce. This advancement is crucial for urban planners who require robust frameworks to predict how shared environments function under varying pedestrian and vehicle demand levels.

The model further builds on behavioral insights highlighted by Uttley et al. (2020), who emphasized the importance of micro-level interactions such as eye contact and group dynamics in priority negotiation. Although our approach is grounded in delay functions rather than direct observation of such cues, it implicitly captures these behaviors by reflecting how vehicles adapt to increased pedestrian presence. This bridging of microscopic behavioral indicators with macroscopic traffic flow performance enhances the precision of capacity estimation.

Importantly, this article demonstrates that the proposed model can be successfully validated using real-world data collected in Prague. The comparison between simulation outputs and observed traffic patterns confirmed the model's ability to realistically reflect pedestrian–vehicle interactions. While existing tools such as agent-based models offer similar capabilities, their complexity often limits practical applicability. In contrast, our model strikes a balance between behavioral realism and analytical simplicity, making it more accessible for urban planners and transport engineers.

Another key implication of the findings is the identification of conditions under which shared space remains efficient. As the results indicate, there is a critical range of pedestrian and vehicle flow intensities within which both user groups can coexist without significant compromises in speed or safety. Beyond this range, either pedestrian comfort or vehicular mobility begins to deteriorate. This trade-off highlights the importance of careful planning and flow regulation in shared spaces, particularly in urban areas with fluctuating demand.

While the model offers valuable insights, certain limitations remain. The delay function is based on aggregated pedestrian density rather than individual behavioral variations. As such, although it is effective for planning purposes, the model may not fully capture nuanced interaction behaviors such as hesitation, distraction, or non-compliance with informal rules. Future research could integrate additional behavioral parameters or real-time trajectory tracking to further improve model accuracy.

In conclusion, the proposed approach provides a practical contribution to the design and evaluation of shared spaces. By identifying quantitative thresholds for pedestrian and vehicle intensities, the study offers a decision-support tool that enables cities to optimize the use of shared environments.

6. CONCLUSIONS

This work closes the key operational gap identified in the Introduction: practitioners lacked a tractable way to translate pedestrian–vehicle interactions into design-ready capacity limits for low-speed shared zones. Consistent with earlier evidence that shared spaces can maintain safety and efficiency—even under heavy, fluctuating demand without significantly impeding vehicular flow—the article delivered the two promised outcomes:

1. *General delay law.* An explicit four-parameter equation links instantaneous vehicle speed to local pedestrian density, forming an analytical bridge between microscopic behaviour and macroscopic design decisions.
2. *Working demonstration.* Applying the law to a 30 m segment of a Prague retail parking lot produced an Ω-curve that tells planners, at a glance, which combinations of pedestrian and vehicle flows keep delay acceptable.

Using a VISSIM–MATLAB calibration loop and real-world observations, the model shows that vehicle delay rises sharply with increasing pedestrian density but plateaus once crowding exceeds a critical threshold. When the Ω-curve is read for a single-lane, 6 m-wide layout subject to the Czech-standard maximum\ of 20 km h, it yields the following rule-of-thumb limits:

- **~700 ped h^{-1} can coexist with 100 veh h^{-1};**
- **at 500 veh h^{-1} the pedestrian ceiling falls to ~400 ped h^{-1};**
- **at 2 000 veh h^{-1} pedestrian flow must stay below ~175 ped h^{-1} to keep mean delay within the 4 s target.**

These figures align with observations on heavily trafficked shared corridors elsewhere (3 432–4 174 veh h^{-1} and 711–1 235 ped h^{-1} moving at roughly 35 km h^{-1} without collapse), confirming the robustness of the envelope under markedly different demand levels.

Calibrating the rules on a behaviourally rich set of artificial scenarios—using a "first-come, first-serve'' conflict rule that best matched field practice—proved essential because on-site data alone lacked the necessary variability. The resulting tool can (i) predict average vehicle speed along a shared corridor, (ii) map space–time density to flag incipient queues, and (iii) output an Ω-curve so designers can test alternative demand forecasts without rerunning full microsimulations.

While the present formulation is limited to single-lane geometries with clear sight-lines, the next step is twofold: (a) gather additional real-world measurements to validate the model repeatedly and establish definitive maximum-low thresholds, and (b) extend the delay law to multi-lane and visibility-constrained contexts.

Moving forward, the authors aim to enhance the proposed model by gathering more data from real-world measurements, which will facilitate multiple verifications of calculations and establish maximum flow thresholds. This approach reinforces the potential for optimizing safety and traffic flow in shared environments.

7. ACKNOWLEDGMENT

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APPENDIX A. SOLUTION OF THE PDE (10) - MATLAB ALGORITHM

Step 1: Initialization

```
n = (Section_length)/dx + 1
solution.k = k0
A = zeros(n,n);
```

Step 2: System matrix

```
for i = 1:n
        alpha(i)=dt/2/dx*v(i);
        beta(i)=(1+dt*dvdx(i));
end
A(1,1)=1;
for i = 2:n-1
        A(i,i-1) = -alpha(i);
        A(i,i) = beta(i);
        A(i,i+1) = alpha(i);
end
A(end,end-1) = -2*alpha(end);
A(end,end) = beta(end)+2*alpha(end);
```

Step 3: Solution

```
t = Δt
while t ≤ T
k = A^-1*solution.k(end,:);
k(1) = q_in(t)/v_in;
solution.k = [solution.k; k];
t = t + Δt;
end
```