A Joint Cellular Automata and Noise Model for Description of Urban Signalized Intersection: A Preliminary Study

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Abstract: - Noise in urban environments is mainly due to road traffic. Whether this outcome can be simulated, the simulation outputs are strongly influenced by localized dynamics, such as in the presence of roundabouts or intersections. In such cases, the classic models encounter difficulties, since they have been built to simulate, at their best, scenarios of free flow. Many alternative models can be used to solve such problems. In this paper, a Cellular Automaton (CA) model for simulating road traffic noise is presented. This model is an extension of a previously developed CA for traffic flow and noise prediction, where a new level of complexity has been introduced. Authors, in fact, report a simplified perpendicular intersection between two single-lane roads, analyzing the traffic and acoustic implications. The model, in fact, has a double nature: on one side, it retains the discrete representation of traffic dynamics and integrates new transition rules governing vehicle crossing, right-turn maneuvers, and conflict resolution between perpendicular flows. The effect of traffic lights is also considered by imposing periodic flow interruptions. On the other side it simulates the Pressure Level (L_P) and the acoustic Equivalent Level (L_{Aeq}), both weighted A, at variable points of an interactive noise map by referring to CNOSSOS formulas and establishment. A set of simulations is carried out by varying traffic density, turning ratio, and signalization conditions. Results highlight the impact of intersection dynamics on noise levels, showing that both turning maneuvers and signal control significantly affect sound emissions, especially in the proximity of the intersection area. The proposed approach provides a flexible and computationally efficient framework for analyzing the acoustic impact of simplified urban road layouts.

Key-Words: - Cellular Automata, Signalized Intersections, Road Traffic Noise, CNOSSOS, Python, Dynamic Noise Mapping.

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1 Introduction

Despite the several efforts of Governments, road traffic noise remains one of the most significant sources of environmental noise in urban and extra-urban areas, [1], [2]. European Union, with the generation of the CNOSSOS framework, aimed at an easier way for simulating and controlling road traffic noise in proximity to sensitive receivers. Nonetheless, more than 20 years later, the situation didn't improve as expected, [3]. A significant number of publications assessing the relationship between high road traffic noise levels and adverse effects on human beings can be easily retrieved in the literature, [4], [5], [6]. Some of them successfully quantified the damage, expressing it in Disability-Adjusted Life Years (DALY), representing the total number of years lost due to premature mortality and years lived with disability (of course attributable to environmental and health risk factors, in this case noise), [7], [8]. Due to this, the capability of modelling the impact of road traffic noise in a given area is still of remarkable importance. While standard models function at their best in simulating free-flow conditions (where vehicles flow without stop-and-go at moderate to high speeds), they fail to varying degrees when approaching more fragmented scenarios, [9], [10], [11]. Standardized prediction models, in fact, are preferably used for large-scale assessments, average traffic conditions, and steady-state assumptions, not adequately capturing the dynamic nature of urban traffic.

In particular, road intersections are critical points in traffic networks, where vehicle interactions, directional changes, and flow disruptions lead to complex dynamics, including queue formation, stop-and-go patterns, and transient acceleration phases. These phenomena have a direct impact on noise emissions and cannot be easily represented using macroscopic approaches, [9], [12], [13]. As possible solutions, microscopic approaches to traffic simulations can provide better results since they can provide, as input, more detailed traffic frameworks as a starting point for the simulation of noise impact. Among the microscopic approaches Cellular Automata (CA) models have proven to be effective in reproducing traffic dynamics through simple discrete rules, while maintaining low computational cost. Starting from the first and pivotal work, [14], in 1992 which is considered to be the first widely recognized application of cellular automata to traffic flow modelling, the potential of such an approach has grown until more recent and performing applications, [15], [16], [17] on simulating traffic conditions not commonly depictable by standard models.

Following this research line, in a previous work, authors [18] developed a CA automata model able to simulate traffic flow on multi-lane roads and to estimate associated noise emissions, including the presence of traffic lights. This model was limited to linear road configurations and did not include the possibility of simulating intersections. The present work aims to further extend this idea by introducing a perpendicular intersection between two one-way single-lane roads with the possibility of inserting a traffic light. The core modeling framework is inherited from [18], with minimal modifications to the appearance of the simulation of videos. More in detail, the code governing the basics of vehicle flow and the Acoustic generation of sound power level and its propagation are retained, while the code lines for new rules are reported here for the first time. More in detail, the model is enriched with specific rules governing vehicle crossing, turn maneuvers, and conflict resolution, as well as the possibility of traffic light regulation. The objective of this paper is to investigate how these additional dynamics influence traffic by conducting parametric simulations in which traffic density, turning ratio, and signalization conditions are systematically varied. From the acoustic point of view, moreover, a detailed comparison between noise pressure levels (L_P) and equivalent noise level (L_{Aeq}) resulting from each simulation in two positions at different distances from the intersection.

The remaining part of the contribution will be organized as follow: in section 2 Material and Methods will be presented, with a particular focus on the improvement of the intersection; in section 3 the results of 12 different simulations will be investigated and compared both from traffic and acoustic point of view, and finally in section 4 conclusions of the study will be reported with limitations and future planned improvements.

2 Material and Methods

In this section, the main modelling framework adopted in this work is presented, with a focus on the extensions introduced to account for the intersection.

2.1 Base CA model

The traffic model adopted in this work is based on a previously developed CA framework that was derived from the classical Nagel–Schreckenberg (NaSch) model and extended to include different vehicle types and traffic light regulation. The road is discretized into cells of fixed length, and time advances in 1-second time steps. Each cell can be either empty or occupied by a vehicle, characterized by its position and discrete speed. Vehicle dynamics follow the standard NaSch update rules, including acceleration and deceleration based on the distance to the leading vehicle, as well as position updates. The model also includes stochastic effects to account for variability in driver behavior, as well as different vehicle categories with distinct dynamic characteristics.

Traffic light regulation can be applied by imposing stop conditions at predefined locations along the road. The microscopic kinematic variables obtained from the CA simulation are used as input to the acoustic model, enabling estimation of noise emission at each timestep. This framework represents a consolidated approach within the line of research on microscopic traffic modelling using cellular automata. The main parameters of the model are summarized in Table 1.

2.2 Mathematical Formulation of the Cellular Automata Model

The whole model is made of a traffic part and an acoustic part. The traffic part is mainly based on the classical Nagel–Schreckenberg (NaSch) cellular automaton model, of which this contribution represents an extended version. Essentially, the road network is discretized into cells of fixed length and time advances in discrete steps of Δt = 1 s. At each iteration, all vehicles are synchronously updated according to the following transition rules.

2.2.1 Acceleration
If possible, a vehicle increases its speed by one discrete unit:

$$v_i(t+1) = \min[v_i(t)+1, v_{max}] \quad (1)$$

$v_i(t)$ is the speed of the vehicle i at time t, and v_{max} is the maximum speed possible.

2.2.2 Collision-Avoidance Deceleration
To prevent crashes when vehicles accelerate, speeds are limited by the available distance to the leading vehicle:

$$v_i(t+1) = \min[v_i(t), d_i - 1] \quad (2)$$

d_i is the number of empty cells between vehicles i and the vehicle ahead.

2.2.3 Randomization
According to the original NaSch formulation, a stochastic slowdown mechanism is introduced, reducing the speed of vehicles by one unit with a probability p according to the formula:

$$v_i(t+1) = \max[v_i(t+1) - 1, 0] \quad (3)$$

This rule is present for accounting for driver variability and non-deterministic traffic behavior.

2.2.4 Position Update
At each iteration, vehicles move forward according to the new speed that has been computed. New vehicles' positions are updated as follows:

$$x_i(t+1) = x_i(t) + v_i(t+1) \quad (4)$$

$x_i(t)$ denoting the position of the vehicle i along the road lane.

2.2.5 Boundary Conditions
Any traffic cellular automata model is forced by the specification of precise boundary conditions, which rule the behavior of vehicles entering or exiting the road limits. In the present work, periodic boundary conditions are adopted, meaning that a vehicle leaving the last cell of the road is immediately reintroduced at the first one. Using this configuration ensures the maintenance of a constant number of vehicles in the whole simulation over time and ensures that traffic density remains approximately constant throughout the whole simulation.

This choice simplifies some aspects of the model, for example, simulating a traffic situation that is static over time. Moreover, it excludes the possibility of simulating the influence of external inflow or outflow conditions. In this way, any variations in the acoustic indicators may be reasonably attributed to the internal dynamics of the model (such as vehicle interactions, lane-changing, turning maneuvers, and signalized intersection effects). The periodic boundary conditions adopted are ruled by the formula:

$$x_i(t+1) \leftarrow x_i(t+1) \bmod L \quad (5)$$

where x_i is the vehicle position at time t + 1, L is the road length expressed in the number of cells, and "mod" denotes the modulo operator, i.e., the remainder of the integer division by the road length L.

2.3 Lane-Changing and Turning Rules
Two of the main extensions compared to the original NaSch formulation are the possibility for vehicles to change lanes and the presence of road interactions (with all the consequent intersection dynamics).

2.3.1 Safety Criterion for Lane Changing
A vehicle is allowed to change lanes only if sufficient space is available in the target lane:

$$g_{ahead} \geq G_{ahead} \quad (6)$$

$$g_{behind} \geq G_{behind} \quad (7)$$

where g_{ahead} and g_{behind} respectively denote the available gaps ahead of and behind the vehicle in the target lane.

2.3.2 Incentive Criterion
A lane change is considered only when it provides a mobility benefit:

$$v_{target} > v_{current} \quad (8)$$

where v_{target} is the expected speed achievable in the target lane and $v_{current}$ is the expected speed in the current lane.

2.3.3 Cooldown Constraint
To avoid unrealistic zig-zag lane-changing behavior, a cooldown mechanism is introduced. After a successful lane change, a vehicle is prevented from performing another lane change for a fixed time interval T_{cd}.

If t_{lc} denotes the last time step at which the vehicle changed lane, a new lane-changing maneuver is allowed only if:

$$t - t_{lc} \geq T_{cd} \tag{9}$$

where T_{cd} is the cooldown period.

In the present implementation, the cooldown is set to 6 iterations.

2.3.4 Turning Probability

To each vehicle approaching the intersection, a turning decision value is assigned according to the prescribed turning ratio p_t:

$$P(\text{turn}) = p_t \tag{10}$$

$$P(\text{straight}) = 1 - p_t \tag{11}$$

The assignment is made before entering the conflict area and remains unchanged throughout the whole maneuver.

2.3.5 Turning Feasibility Condition

A turning maneuver can only be executed when sufficient space is available in the destination branch of the intersection:

$$g_{target} \geq g_{min} \tag{12}$$

where g_{target} is the number of free cells in the target direction.

2.4 Acoustic framework

The acoustic component follows the CNOSSOS-EU formulations, [19], [20]. The total sound power level of each vehicle is calculated as the energetic sum of rolling and propulsion noise contributions:

$$L_{w,tot} = 10\log_{10}\left(10^{L_{w,roll}/10} + 10^{L_{w,prop}/10}\right) \tag{13}$$

where $L_{w,roll}$ is the rolling noise component and $L_{w,prop}$ is the propulsion noise component.
The total sound power emitted by all vehicles during a simulation frame is:

$$L_{w,frame} = 10\log_{10}\left(\sum_{i=1}^{N(t)} 10^{L_{w,i}(t)/10}\right) \tag{14}$$

where $N(t)$ is the number of vehicles present in the simulation at time t.

Assuming free-field propagation, sound pressure levels at a receiver located at a distance d are computed as:

$$L_p(d) = L_w - 10\log_{10}(d) - 11 \tag{15}$$

This formulation allows the direct coupling between traffic dynamics, vehicle trajectories, and resulting acoustic indicators.

2.5 Road modelling

The simulations reported in this work consist of a simplified road intersection defined by the perpendicular crossing of two one-way single-lane roads of equal length, each composed of 100 cells (750 meters).

2.5.1 Geometry and Representation

The two road segments intersect at a central area represented by a set of cells shared by the two traffic streams. Each road maintains its own longitudinal discretization, while the intersection region defines a conflict zone where vehicles from different directions interact.

Table 1. Parameters of the CA model

Parameter	Value	Description
Cell length	7.5 m	Spatial discretization of the road
Time step	1 s	Temporal resolution of the CA model
Road length	100 cells	Length of each road segment
Number of lanes	1	Single-lane per direction
TW (two-wheelers)	15%	% of TW over total traffic
L (light vehicles)	60%	% of L over total traffic
M (medium vehicles)	15%	% of M over total traffic
H (heavy vehicles)	10%	% of H over total traffic
TW length	1 cell	
L length	1 cell	
M length	2 cells	
H length	3 cells	
TW max speed	2 cells/s	~50 km/h
L max speed	2 cells/s	~50 km/h
M max speed	2 cells/s	~50 km/h
H max speed	2 cells/s	~50 km/h
Density	0.1 – 0.3	Cells occupied by vehicles over total cells
Traffic light cycle	30 s	Total duration of the traffic light cycle
Red phase	15 s	Duration of red ligth phase
Turning ratio	0.1 – 0.5 – 0.9	Probability of right turn

Source: created by the authors.

Figure 1 shows the road geometry used for the simulations of the work presented here.

2.5.2 Vehicle Interaction and Priority Rules

In the absence of traffic light control, vehicles approaching the intersection are subject to priority rules based on the availability of free cells in the downstream direction and, when applicable, in the turning direction. In particular, a vehicle is allowed to enter the intersection only if a sufficient number of cells ahead are free. This condition is evaluated using a configurable parameter that specifies the number of cells required to safely complete the maneuver. When turning movements are enabled, the same condition is applied to the target direction, ensuring that vehicles do not enter the intersection unless sufficient space is available.

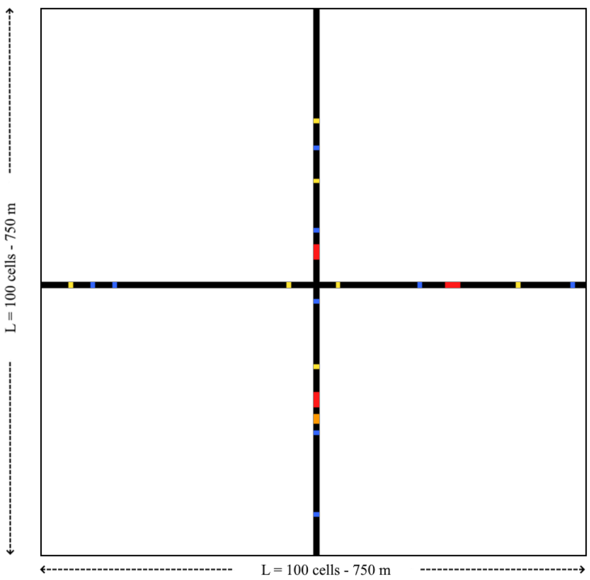

Fig. 1: Roads geometry used for the simulations
Source: created by the authors

The corresponding rule is then the following. Being g_f the number of free cells ahead of the conflict area and G_{min} the minimum required safety gap, the entrance condition is defined as:

$$g_f \geq G_{min} \quad (16)$$

with g_t as the number of available cells in the destination direction. For turning vehicles, the same condition is also checked at the target branch of the intersection. If a vehicle does not fulfill the requirements, it remains queued before the intersection zone.

2.5.3 Traffic Lights Regulation

When traffic lights are active, they regulate vehicle entry into the intersection, eliminating direct conflicts between perpendicular flows. The signal cycle adopted in this work is the same as in the previous study, consisting of alternating phases that allow traffic flow in one direction while stopping the perpendicular stream. During the red phase, vehicles accumulate in queues upstream of the intersection, while the green phase generates acceleration waves as vehicles restart their motion.

2.6 Model Parameters

The main parameters of the implemented CA model are summarized here in order to provide a clear correspondence between the discrete simulation framework and real-world traffic conditions. Each cell represents a longitudinal road segment of 7.5 m, corresponding approximately to the average vehicle length plus a safety gap. Time is discretized into 1-second steps, ensuring consistency with the temporal resolution used in the acoustic model. Vehicles are represented in different categories (two-wheel, light, medium, and heavy), each characterized by specific dynamic properties and occupying a variable number of cells based on their length. Traffic density is defined as the ratio between the number of vehicles and the total number of cells composing the road segments and is assumed to be uniform across both intersecting roads. The traffic light operates according to a fixed cycle, consistent with the previous implementation, defined by a total cycle duration of 30 s, divided into 15s of red and 15s of green. During the red phase, vehicles must stop before entering the intersection, leading to queue formation and subsequent acceleration when the light turns green. These parameters provide a consistent framework for linking the discrete CA representation to realistic traffic conditions while maintaining computational efficiency.

2.7 Simulation Setup

Simulations have been performed by varying three key parameters: traffic density, turning ratio, and the presence or absence of traffic light control.

Two values of traffic density have been considered (0.1 and 0.3), representing moderate and high traffic conditions. The turning ratio has been varied between low, medium, and high values to assess the effect of directional changes on traffic dynamics. A total of 12 simulations have been carried out, combining all the parameters, as reported in Table 2. Acoustic indicators have been evaluated at two receiver positions, defined in Cartesian coordinates with respect to the simulation domain: a first receiver located close to the intersection and a second one positioned further away, to assess the spatial variability of noise levels.

2.8 Computational Implementation

The simulation framework has been developed entirely by the authors in Python. The code was written from scratch, following a modular structure to ensure flexibility and ease of extension.

All simulations were performed using Python 3.10 within the Visual Studio Code (VSC) development environment. The implementation relies on widely used scientific Python libraries. In particular, *NumPy* was employed for efficient numerical computations and array-based operations, while *SciPy* provided additional numerical tools. Data processing and analysis were supported by *Pandas*, and *Matplotlib* was used for visualization and post-processing of simulation outputs.

In addition, the *h5py* library was used to efficiently store and handle large simulation datasets, enabling structured data management and fast I/O operations. The computational experiments were carried out on a workstation equipped with an Intel® Xeon® W3-2423 and 32 GB of RAM, which ensured stable performance during simulations involving multiple scenarios and time-resolved acoustic calculations.

3 Results and Discussions

In this section, the results obtained from the application of the extended cellular automata model to a simple perpendicular intersection are presented and discussed. Simulations have been performed by varying three main parameters: traffic density, turning ratio, and the presence or absence of a traffic light (see Table 2 for details), and investigating the noise outputs. Roads intersect, while the second was far away.

Table 2. Settings of the scenarios simulated. Source: created by the authors.

Simulation #	Traffic light	Density	Turning ratio
1	Yes	0.1	0.1
2	Yes	0.1	0.5
3	Yes	0.1	0.9
4	Yes	0.3	0.1
5	Yes	0.3	0.5
6	Yes	0.3	0.9
7	No	0.1	0.1
8	No	0.1	0.5
9	No	0.1	0.9
10	No	0.3	0.1
11	No	0.3	0.5
12	No	0.3	0.9

Source: created by the authors

In Figure 2, the positioning of the receiver is reported. Please note that the density (expressed as the number of occupied cells over the total cells of the road) is the same for both the crossing roads. The turning ratio is expressed as the number of vehicles that turn right at the crossing point over the total, and it's equal for both roads.

The analysis focuses on the comparison of acoustic indicators, namely sound pressure level L_P and equivalent level L_{Aeq} evaluated at two different receiver positions located at increasing distances from the intersection. In Figure 2, the positioning of the two receivers is shown.

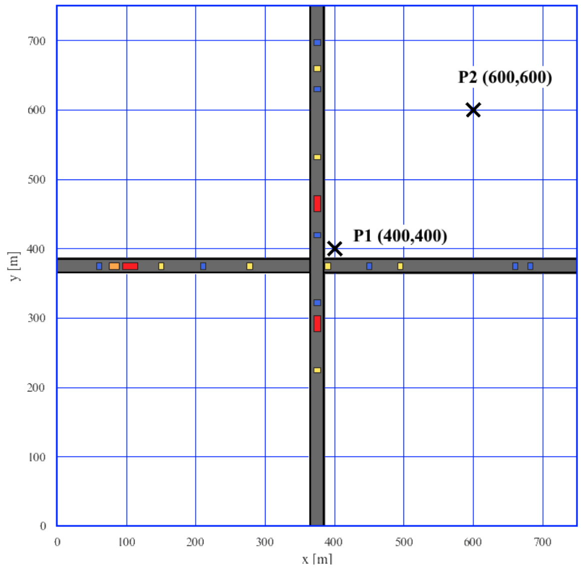

Fig. 2: Sensible receiver points where the impact of traffic has been investigated
Source: created by the authors

Rather than reproducing a specific real-world case, the objective is to assess the model's sensitivity to the selected parameters and investigate how different traffic configurations affect noise emissions in the presence of an intersection.

3.1 Effect of Turning Ratio

The turning ratio represents the proportion of vehicles making right turns at the intersection and plays a significant role in shaping traffic dynamics. The turning of vehicles, in fact, is determined by precedence rules that must be followed when a car is entering the space between the roads. The main result from the noise point of view, anyway, is similar for all the turning ratios. Specifically, with the help of Figure 3, the trend over time of the overall L_W value is shown for simulation 1 (top), 2 (middle), and 3 (bottom). The trends are very similar, indicating that no significant variations in traffic are reported when the number of vehicles turning right at the intersection increases. Whether this may sound strange, three considerations must be remarked. First, at this stage of the development of the research, the rules for avoiding crashing at the intersection are the same for vehicles running straight. In fact, when there are enough free cells to occupy the intersection, the cars are allowed to enter, and the other cars coming from the other lane slow down or stop. Consequently, the slowing down is the same, and no significant differences are expected. Second, vehicles turn only in one direction, depending on the road they are on. Again, this means that the standard rules of priority for vehicles going straight are sufficient to describe the phenomenon of turning. Thus, vehicles occupy the intersection for the same amount of time turning right or continuing straight. The occupancy of the intersection carriages is, of course, augmented when there are multiple turning options available, which at the time was not allowed.

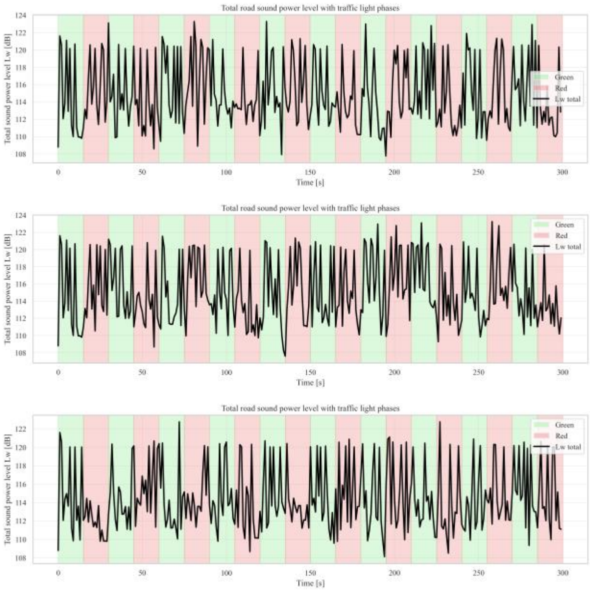

Fig. 3: L_w values of simulations 1 (top), 2 (middle), and 3 (bottom) with increasing turning ratio: 0.1, 0.5, 0.9

Source: created by the authors

Third, the simple geometry of the intersection does not imply a difference in the number of cells that cars must run when turning or when not turning. Since the overall L_w values do not show great differences at varying turning points, it is not expected that L_P measured at the two sensitive spots behave differently. Data reported in Table 3 confirms such a hypothesis.

Table 3. Mean acoustic power level (L_W) and equivalent level (L_{Aeq}) at the chosen points

Simulation #	Mean L_W [dBA]	L_{Aeq} point 1 [dBA]	L_{Aeq} point 2 [dBA]
1	92.2	57.5	42.9
2	92.2	57.8	43.1
3	92.4	56.7	42.3
4	87.9	54.4	40.4
5	86.3	53.6	39.0
6	86.8	53.9	39.5
7	94.1	56.3	42.2
8	94.0	57.6	42.2
9	94.1	56.3	42.2
10	87.7	53.5	39.2
11	88.4	54.2	39.8
12	91.2	55.0	41.2

Source: created by the authors

3.2 Effect of Traffic Light

The presence of a traffic light introduces periodic interruptions to traffic flow, generating stop-and-go conditions that significantly affect both traffic dynamics and noise emissions. Comparing signalized and non-signalized scenarios, the introduction of the traffic light leads to a general increase in the average acoustic levels (L_W). As reported in Table 4, a difference in L_W levels is always observed when comparing simulations that differ in the presence/absence of a traffic light. Specifically, for simulations with 0.1 of vehicle density, a difference of circa -2 dBA is observable.

Table 4. Difference of mean L_W with and without traffic light

density	turning ratio	Mean L_W with TL	Mean L_W without TL	diff.
0.1	0.1	92.2	94.1	-1.9
0.1	0.5	92.2	94.0	-1.8
0.1	0.9	92.4	94.1	-1.6
0.3	0.1	87.9	87.7	0.2
0.3	0.5	86.3	88.4	-2.1
0.3	0.9	86.8	91.2	-4.4

Source: created by the authors

For simulations with a a 0.3 vehicle density difference, it is higher (from -2.1 to 4.4 dBA) for 0.5 and 0.9 turning ratios, and lower (only 0.2 dBA) for the simulation with a 0.1 turning ratio. This behavior suggests that traffic density influences the acoustic response of the system in a non-trivial manner. The general tendency of having lower L_W when the traffic light is on is consistent with the function of the traffic light itself, which should avoid jams due to the contemporary presence of too many vehicles on the same road sections that have to stop and go multiple times to solve the bottlenecks. Nonetheless, the choice of traffic light phase duration and the correct alternating of red and green cycles could contribute even more to regulating the traffic and to mitigating not only transportation aspects (jams), but also acoustic ones. At this preliminary point of the investigation, as already stated in the previous paragraph, the authors did not search for the most realistic and convenient setting of parameters from the transportation point of view. Rather, it is interesting to note how the acoustic part of the model can capture subtle differences in traffic composition and/or evolution, translating them into noise effects.

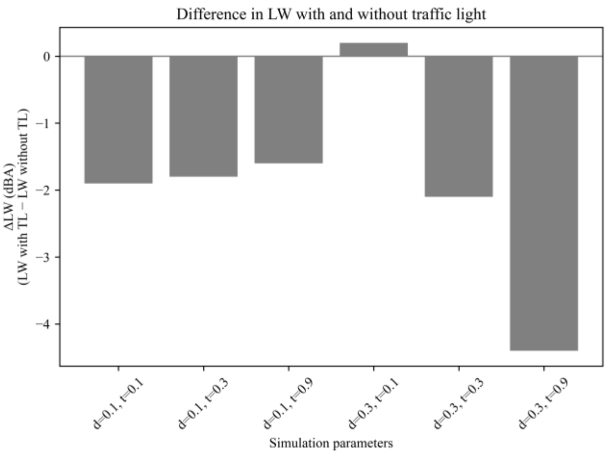

Fig. 4: Difference of L_W for the same simulation with and without a traffic light
Source: created by the authors

3.3 Effect of Road Density

Traffic density is the last key parameter investigated in relation to its potential influence on the acoustic output of the system. Generally, data show that the increase in density (from 0.1 to 0.3) leads to a decrease in the overall noise power level (L_W) (see Table 5). The effect is clear: the contemporary presence of more vehicles on the road leads to a general decrease in overall speed and acceleration, which results in a lower noise contribution (as confirmed from the last columns of Table 5 itself, reporting the average speed of vehicles according to each simulation).

Table 5. Mean L_W at different densities

density	turning ratio	Traffic light	Mean L_W [dBA]	Mean speed [km/h]
0.1	0.1	yes	92.2	44.9
0.3	0.1	yes	87.9	27.31
0.1	0.1	no	94.1	51.82
0.3	0.1	no	87.8	26.80

Source: created by the authors

It should be emphasized that this apparently contradictory result requires, for a proper interpretation, a strong assumption of the adopted modelling framework. In the present model, in fact, vehicle noise emissions are estimated solely by the CNOSSOS methodology, whose acoustic formulation is strictly and directly linked to instantaneous vehicle speed. Consequently, the significant reduction in average speed of all the roads (due to increasing density at higher traffic) may compensate for, or even outweigh, the increase in the noise associated with the larger number of simultaneously circulating vehicles. Similar observations have been reported in previous studies, highlighting how traffic dynamics and transient traffic states significantly influence road traffic noise generation and assessment, beyond simple traffic volume indicators, [21], [22]. Another main point is that on a congested road, several noise sources increase aside from the one contemplated by the CNOSSOS model (speed and acceleration). Honking noise, for example, can become predominant, especially in an urban context like the one presented here, [23], [24]. The idling noise also becomes very relevant, but at this point, such aspects have not yet been incorporated into the CA model and therefore cannot contribute to the simulation. In Figure 5, a comparison is reported: LW over time of two simulations having different (increasing) densities of vehicles. For clarity, authors choose simulations without traffic lights, which naturally present more oscillations (especially at light color change) that make the effect of density less intelligible.

3.4 Spatial Variability and Receiver Comparison

Finally, the spatial variability of the acoustic field has been investigated by evaluating sound levels at two receiver positions: one located near the intersection and one at a larger distance. Points have been identified with coordinates on the maps, considering the lower-left point as the origin of the axes.

Results are very interesting, since they show two aspects in contemporary society. The first aspect to be noted is that the L_P is lower at the further point. Such evidence, even if it's obvious from the physical point of view, confirms the proper functioning of the model, especially in the part of the code related to the acoustic mapping of the neighbors of the road structure. The second aspect is that the L_P over time presents significant fluctuation at the receiver point near the intersection, while it is more stable at the second point. These oscillations arise from the stop-and-go of vehicles occupying the intersection space and from managing the rules to avoid crashes. Such accelerations and decelerations greatly contribute to the variation of the power level (and the consequent pressure level measured at the given distance), but they are not appreciated when we move forward from the intersection.

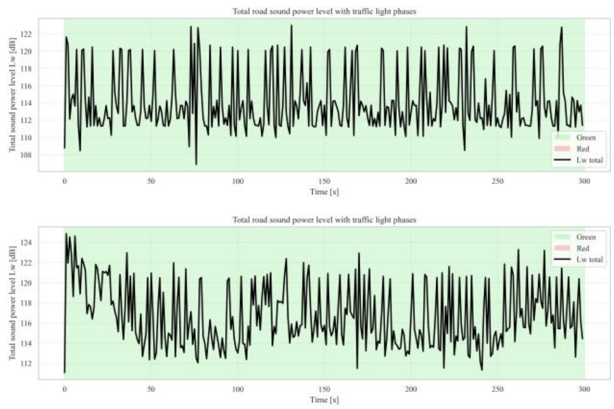

Fig. 5: Difference of L_w for the same simulation at increasing vehicle density
Source: created by the authors

Figure 6 clearly highlights this effect. The authors chose to report a comparison of simulations without a traffic light, where these oscillations are even more accentuated (but surely a contribution to the phenomenon is the alternating of the red and green lights). As for the equivalent levels, they exhibit a clear difference in behavior. Nonetheless, since the authors only implemented a simple linear propagation formula for this preliminary work without the presence of any obstacle or diffraction law, such an aspect can only reveal the goodness of the model in the computation of the basic noise aspects. Having the possibility to compute L_P in a given location over time, anyway, led to the generation of dynamic noise maps, representing the acoustic influence over a 750 × 750 square meters area. Within such a time-dependent framework, the model allows the simulation of the evolution of noise impact at any point where a sensitive receiver could be located. Although acoustic mapping is not the primary focus of the present study, it always represents a valuable aspect in the acoustic investigation of road traffic scenarios, and for this reason, it has been implemented in this approach.

By visualizing the spatial distribution of sound levels, a more intuitive interpretation of the relationship between traffic dynamics and noise emissions can be achieved. In the presented case, moreover, the proximity of the intersection can be evaluated in relation to the remaining roads, to evaluate how the traffic dynamics can be influenced.

Generated maps are, of course, dynamic due to the inner nature of the CA model. L_P over the grid, in fact, is generated frame-by-frame (second-by-second), resulting in a continuously evolving map. An example of this representation is shown in Figure 7, where a single timestep from the simulation illustrates the spatial distribution of noise levels relative to vehicle positions.

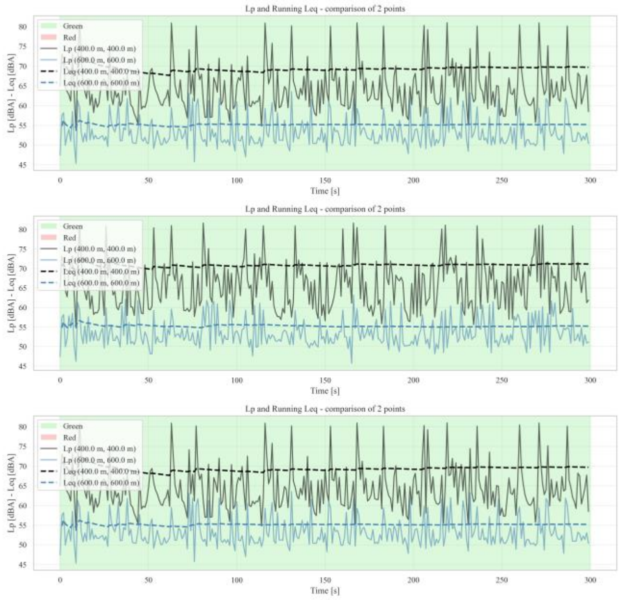

Fig. 6: L_P and L_{Aeq} at two different sensible receivers. The black lines are related to the receiver near the intersection, and the cyan one to the receiver far away from the intersection
Source: created by the authors

In Figure 7, the grids used for the spatial organization of the map are visible. Such grids also represent the discretized spaces where the L_P values are computed. From an application perspective, the generated maps can be useful for several cases. They could allow, for example, the simulation of the effect of road traffic noise in areas that are not yet urbanized but may be subject to future development. In this context, the model can support preliminary environmental assessments by estimating the potential acoustic impact of planned infrastructures before their realization. Moreover, maps could be used to orient traffic management strategies by highlighting the effect of different traffic configurations on specific locations. This last aspect can be very relevant in the case of the presence of particularly sensitive receivers (schools, hospitals, natural areas, archaeological sites), where minimizing noise exposure is a key objective and can also be compelled by law, [1], [25], [26], [27], [28]. All in all, while the mapping component represents only one aspect of the proposed model, it significantly enhances its practical applicability by linking microscopic traffic behavior to spatial noise distribution in a clear and quantitative manner.

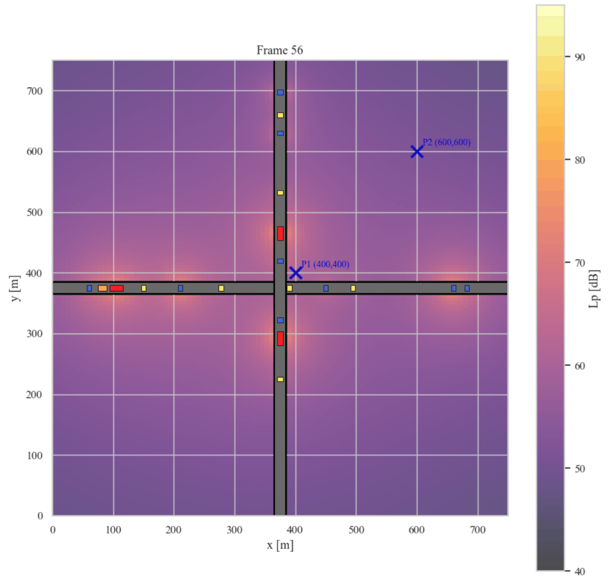

Fig. 7: Single frame of the interactive maps reporting the evolution over time of both the traffic and noise aspects of the simulation
Source: created by the authors.

4 Conclusion

In this work, a cellular automata model is presented based on the classic Nagel-Schreckenberg approach, but implemented with the possibility to simulate a simplified perpendicular intersection between two single-lane roads. The rules for the vehicle interaction in proximity to the intersection (priority management, right-turn maneuvers) are studied by themselves or in relation to the presence of a traffic light. Despite the simplified geometry, the proposed framework demonstrates its ability to reproduce key dynamic features typical of urban intersections, including traffic conflicts, queue formation, and stop-and-go patterns. The results of the parametric simulations highlight the roles of turning ratio, traffic density, and signalization in determining acoustic levels. In particular, it has been shown that the turning coefficient (i.e., the number of vehicles over the total turning to the right) does not influence the acoustic impact of the simulation. Presence/absence of traffic light and, moreover, density of the roads introduce additional variability in traffic flow, which directly translates into fluctuations of noise emission, especially in their immediate proximity. Although the analysis has been performed on a simplified configuration, the model demonstrates its capability to capture the interplay between traffic dynamics and noise generation in more complex geometries than linear road segments.

The presented work, of course, has its limitations. The geometry used to simulate the intersection is the simplest one can imagine, and the priority rules are significantly schematized. Roads are built to simulate a single lane, and the turning can only happen on the right side. As for the acoustic framework, the noise estimation relies on the CNOSSOS model, but it neglects background and honking noise, which are frequent, especially in urban scenarios. Therefore, the simulated sound levels reflect only the noise contribution generated by the modeled traffic flow and cannot integrate, at this level, additional urban sound sources like honking, pedestrian activity, and background environmental noise. The L_P estimation, moreover, happens by a simple geometric propagation formula, without considering any phenomenon related to the presence of obstacles (other roads, buildings). Future developments, therefore, will include the extension to multi-lane intersections, the introduction of more complex propagation aspects, and the addition of other sound sources, to obtain even more realistic decision-driven simulations of urban and extra-urban road traffic noise scenarios.

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