City Infrastructure Evaluation using Urban Simulation Tools

R. Dostál, O. Přibyl and M. Svítek

Abstract—**With ever-changing cities and growing populations it becomes progressively more difficult to assess which infrastructural changes are beneficial and which are possibly destructive long-term. It is almost impossible to find experts that understand the wide range of aspects surrounding smart cities as well as their interrelationships. Decision makers need a tool that helps them to set certain policies and evaluate their impact on key performance indicators (KPIs). This paper presents a multi-criteria evaluation method based on assessing infrastructural changes in the city combining different modeling tools to gather sufficient data to assess and evaluate different alternatives. The proposed approach is demonstrated on a case study from Prague 6, Vítězné náměstí.**

Index Terms—**Transport modeling, Environmental modeling, KPIs (key performance indicators), Mathematical modeling, Smart City, Urban simulation.**

I. Introduction

THE current problem in most cities is the lack of space available for larger infrastructural changes in more densely populated urban areas. The pressure on both the city/borough and the potential investors/developers to make prudent decisions in choosing an option is rather high.

In order to reach an optimal decision, stakeholders need to evaluate costs and benefits. Evaluating the costs usually isn't a problem, as it is often part of an offer made (tender). This paper addresses the task of evaluating benefits of possible adjustments to city infrastructure, be it a new building, change in public space, change in the function of the area, organizational changes, traffic management changes or other important transformations. Even though there are many tools for evaluating different use cases or scenarios for any given development project, they are usually not efficient enough when aiming at maximum objectivity.

The main objective is to ensure the highest possible quality of life (QoL) for all citizens in any given city in addition to optimizing and managing the costs of proposed changes. For us, in the first step, quality of life is represented by so-called livability (trying to capture the objective quality of life) as opposed to satisfaction as a subjective view over quality of life [1].

The design of the public space and the infrastructure (its functionality, traffic, environment etc.) are the basic aspects that need to be considered when evaluating optimal solutions [2]. Should this problem be viewed in the scope of a very relevant Smart City, the conclusion is reached that every such problem needs to be evaluated from multiple points of view within the complex system [3],[4] and [5].

The evaluation is based on several software models with the capacity to model events within each examined field of study. These fields of study encompass four main themes: Urbanism, Transportation, Energy and Environment.

In this paper a complete integration would entail obtaining KPIs from multiple fields of study and subsequently combining them in a simple tool that offers a transparent method of evaluating case scenarios.

At present, the strongest connections are found between Mobility/Transportation and Environment (Environment being affected by traffic emissions). The integrations are based on using KPIs from Mobility modelling as inputs to Environmental modelling.

In existing assessment methods, a weight is assigned to each criterion or to every field of study and then the outcome is represented by a weighted sum of the parameters [6], [7] and [8]. It creates a system that is opaque and allows for unwanted effects.

This paper presents a new Interdisciplinary Assessment Method (IAM) that overcomes these problems and provides decision makers with more user-friendly evaluation of city infrastructure.

II. Interdisciplinary Assessment Method (IAM)

With the goal of creating an easy to read and understand approach for assessing city infrastructure, one must ensure the steps that need to be taken are concise. The methodology is based on choosing the proper thresholds for each evaluated interdisciplinary KPI and monitoring how often any critical points are exceeded.

A. Description

Step-by-step guidelines to the Interdisciplinary Assessment Methods (IAM) method are necessary to ensure the methodology is used correctly. There need not be any integration at all as all KPIs are evaluated separately. The integration does however improve this evaluation process

R. Dostál is with the Czech Technical University in Prague, Faculty of Transportation Sciences, Prague, 110 00, Czech Republic (e-mail: dostarom@fd.cvut.cz).

O. Přibyl is with the Czech Technical University in Prague, Faculty of Transportation Sciences, Prague, 110 00, Czech Republic (e-mail: pribylo@fd.cvut.cz).

M. Svítek is with the Czech Technical University in Prague, Faculty of Transportation Sciences, Prague, 110 00, Czech Republic (e-mail: svitek@fd.cvut.cz).

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greatly, as it connects all the areas of expertise making their correlations easier to understand.

The proposed IAM consists of the following eight steps:

1) Describing the city infrastructure that is to be evaluated and dividing it into segments and types, e.g. residential, industrial etc. *(In our example it would mean road segments, but these can also be building blocks or other parts of the public space. It is paramount to include any area that is to be measured and evaluated.)*
2) Setting a threshold for each KPI for different segments and types of the infrastructure which adhere to the basic threshold, which can be described as the first limit that should not be exceeded and the critical threshold described as a second critical point that must not be exceeded under any circumstances. *This is the core step connected to a Smart City equalizer described later. Continuing the example of road infrastructure, this would mean stating that for residential areas the* PM_x *emission should not exceed 100 g/km/h (first threshold) and must not exceed 1,000 g/km/h (critical threshold) etc.*
3) Choosing one segment of infrastructure with an assigned type and set thresholds. *The evaluation process goes through every segment. In the article the focus is on describing this method referencing one segment for simplicity; however, all segments need to be evaluated.*
4) Running simulations and determining if any KPI was exceeded for each time period and all KPIs for the chosen part of infrastructure. Recording how much a threshold was breached for statistical purposes and for how long the threshold was exceeded. *This is critical step in the process, as exceeding the limit threshold is integral to the evaluation.*
5) Calculating the percentage of all time periods throughout the day, where a KPI's threshold was exceeded. *This percentage allows for severity interpretation.*
6) Repeating the steps 2-4 for the entire infrastructure to include each segment and every scenario.
7) Dealing with extreme values. *If a critical threshold is exceeded the process needs to be re-evaluated and errors need to be found*.
8) Comparing scenarios and re-evaluating the thresholds (equalizer) to reach the optimal solution *(checking if set thresholds that can be understood together as the equalizer can be shifted).* The comparison can be both visual and statistical.

B. *KPI Visualization*

The aim is to take into account the impact that all present criteria (or KPIs) have. The team came to the conclusion that having a cumulation of criteria with different weights inevitably leads to negligence in regard to each criterion in opposing scenarios (the customer might not realize that some important thresholds were exceeded in the event that all the KPIs were simply converted into one number). The optimal solution is to have no weighting, focus on each individual criterion and to let the real values and their thresholds drive decision making.

This is simply illustrated for one value (presented as a KPI) being observed and recorded (the example being PM_x emissions). For this KPI there is a limit of 100 g/km/h of any infrastructure segment. Anything below this limit (or threshold) is in the acceptance region. If any given value is within the acceptance region, it is evaluated as accepted and no threshold breach is being recorded.

This basic principle becomes slightly more difficult when there are more KPIs involved, which is usually the case. This creates a matrix of KPIs each varying in values. A graphical representation of KPIs and their thresholds is shown on Fig. 1.

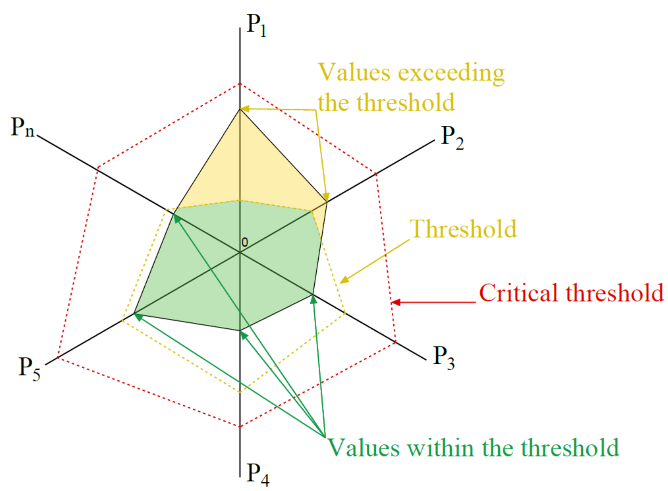

Fig. 1: Six parameters (or KPIs) with values from 0 to R.

$P_1, P_2, ..., P_n$ represent "parameters" (or KPIs with particular values). Dotted lines visualize thresholds (limits); the yellow threshold (being the basic threshold that need to be determined for each type of segment) determines the acceptance region mentioned above; the red threshold (critical threshold) shows area that is not to be reached or breached. The desired state for all of the KPI's values shall be within the green region (also known as the acceptance region). The IAM; however, focuses on monitoring the yellow areas.

This cannot be evaluated just for a single time interval, but rather through the entire predefined measurement period. The number of KPIs is not limited. Since the KPIs typically do not depend on any other variables but time, each can be represented in one dimension. The important information is whether the boundary (threshold) was exceeded or not. The second dimension would be time here. The previous figure in the context of time is depicted in Fig. 2.

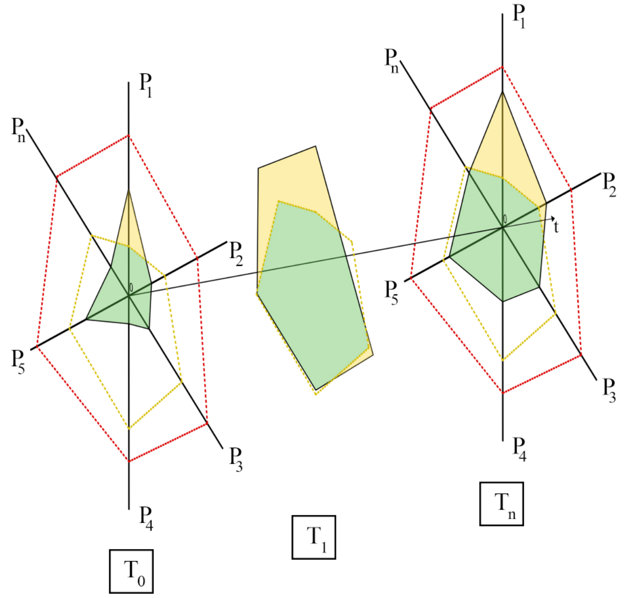

Fig. 2: Six parameters (or KPIs) varying with time.

Contrary to Figure 1, here the evolution of the recorded KPIs over time is depicted. In reality, no visual representation of this process in necessary. This is, however, the best way to depict the acceptance regions for more than one KPI and their variation over time.

C. *KPI Prediction Diagnostics*

Let us look at the prediction diagnosis next. Fig. 2 demonstrates how KPIs exceeding a threshold in time can be observed. This can be also utilized for a prediction diagnostic shown in Fig. 3.

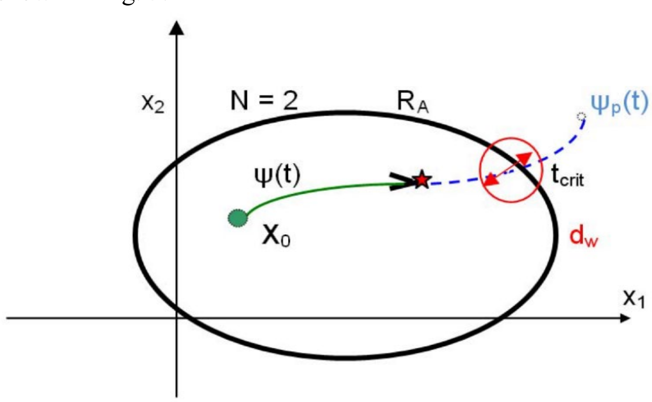

Fig. 3: In Time Warning on the base of prediction diagnostic – Ideal Case [9]

Suppose that the trajectory of life curve $\psi(t)$ is known up to the certain point denoted in Fig. 3 by red asterisk ★ . At this point the further extension of $\psi(t)$ is started to be predicted (dotted blue line $\psi_p(t)$ in Fig. 3).At the moment when this prediction approaches the boundary of the region of acceptability (RA) at the near edge of the warning distance d_w the warning procedure has to be started. [9] and [10]

This requires a repetitive collection of data (or continuous stream) and repetitive modeling of all systems involved [11].

The benefit would be the possibility to observe real changes in the system and predict when critical values (or thresholds) are going to be breached. Sufficient reliability of such predictions must be reached in order to properly utilize systems in this manner [10]. Therefore, the prediction must be done early enough to take action averting unwanted situations. Such an extension to the proposed approach would then allow reliability in that the chosen scenario is kept stable.

D. *Evaluation of KPI Acceptance*

The next step is to determine the percentage of the time that the boundary was exceeded for. This percentage (for each individual KPI) corresponds to the performance (quality) of the selected network under specific conditions. If needed, the percentage can be further categorized into 5 grades, each comprised of a 20 % increase from 0 %to 100 %. This scale can then be used to evaluate the entire network (infrastructure). For visualization purposes, each grade can be further assigned a different color. With time percentage reporting, the visual representation is important for the evaluation, not only to explain the principle.

The greatest benefit of this approach is its transparency. No visualization is necessary before the final evaluation of the network. The KPIs may be more easily understood when sorted in a table with basic information for each KPI (such as unit and the thresholds) and all the recorded values through the entire evaluated period. An example is provided in Table I.

TABLE I
EXAMPLE OF A TABULAR DATA EVALUATION

Segment ID 001				Hours			
KPIs	Units	Threshold (example)	Critical threshold	7	8	9	...
Traffic volume	veh/h	1 500	2 000	1 753	1 690	1 251	...
Speed (higher is better)	km/h	15	1	14	23	46	...
Fuel consumption	l/km/h	400	4 000	413	387	300	...
CO_2	g/km/h	750 000	2 000 000	800 073	653 215	593 333	...
PMx	g/km/h	100	1 000	146	107	78	...
NOx	g/km/h	4 000	40 000	4 523	4 372	3 667	...
Boundary exceeded		47 %	0 %				
Segment evaluation		3					

In Table I, a complete depiction of the evaluation process for a hypothetical case is provided. There are six exemplary KPIs (Traffic volume, Speed, Fuel consumption, CO_2, PM_x, NO_x – more can be easily added) with set thresholds and critical thresholds. The colored values on the right signify if the measured average value was within the threshold (yellow is for value exceeding a threshold; green is for the value remaining within the acceptance region; red would be for exceeding the critical threshold). Below the individual threshold values there is a summary for each segment in percentage (what percentage of time any threshold was exceeded for this particular segment). Similarly, the critical threshold has a percentual statistics below. Below these percentages, there is the assigned grade (3 in this case), that may later be converted into a color scheme for the entire infrastructure.

E. *District Evaluation Trough Equalizer*

The process of determining the thresholds (at least the basic threshold – yellow) is not simple, yet needs to be justifiable. Through an expert decision, political decision or surveys, so-called *Public Space Equalizer* or *Smart City Equalizer* can be created. The equalizer describes KPIs for any given part of the city. Since it is easy to visualize, it is also simple to present and to discuss. This idea can be taken a step further, by creating an interface where one simply drags the values in the equalizer. Thereafter, either an optimal solution is reached, or one may understand the landscape further and prepare for changes. An example of how a Smart City equalizer might look like is represented below in Fig. 4. This interface would be linked to the workings of the model and basically convey all changes directly to the table above.

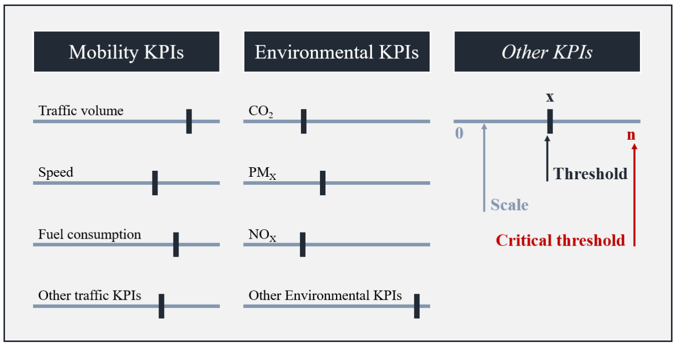

Fig. 4: Example of a Smart City Equalizer.

There are several means of choosing the thresholds (as hinted above). One should turn to legally accepted norms such as ČSN (Czech Technical Standard) in Czech Republic and other expertly created materials first (a good method in regard to both, mobility and environment). If the desired value is not found through these, or if the detail lacks (e.g. different area types are not recognized) one should then seek expert opinion, request a political decision or alternatively attain public opinion).

F. Extreme Values

The last point to be addressed is extreme values. In a situation where time thresholds are the only metrics considered, one might neglect some extremes that should be deliberated. To resolve this a simple arithmetic can be used. One would analyze the data available and calculate the average of the differences between exceeding values and the critical point, then calculate standard deviation. This allows for more granularity regarding volatility for all the data-points. An example of such analytical evaluation is shown in Table II. This can be done for each individual segment, for the entire infrastructure, or for certain types of segments which share the same KPI thresholds.

This would be the same table as Table I where there is no longer visualization of individual values. There is a statistical evaluation of the entire evaluated period. "Average % over limit" would show the percentage of the entire evaluated period an individual KPI's threshold was exceeded. The "Difference average" describes the average value of difference between threshold and exceeding value from every time interval. Lastly "Standard deviation" is a standard deviation from the mean for the calculated "Difference average". These would be the basic statistics needed to describe the extreme values.

Table II
Statistical analysis of the evaluation.

Segment ID 001				Statistics		
KPIs	Units	Threshold (example)	Critical threshold	Average % over lim.	Difference average	Standard deviation
Traffic volume	veh/h	1 500	2 000	23 %	73	39
Speed (higher is better)	km/h	15	1	17 %	4	1
Fuel consumption	l/km/h	400	4 000	7 %	27	6
CO_2	g/km/h	750 000	2 000 000	17 %	130 134	62 902
PMx	g/km/h	100	1 000	31 %	31	18
NOx	g/km/h	4 000	40 000	29 %	1 163	649
Boundary exceeded		47 %	0 %			
Segment evaluation		3				

The second step was the introduction of the second threshold (described as "Critical threshold" in Fig. 1). The exceeding of this threshold means a warning. Two events might be happening: 1. there is an error in the model or evaluation or 2. some of the KPIs have very high values. In either case, a more in-depth examination is necessary. The critical threshold needs to be set to a relatively high value to ensure it is not exceeded in 99 % of cases.

III. Case Study

A. Assessment Scenarios

As stated in the introduction, the IAM can include any number of areas of expertise and any number of KPIs. In order to demonstrate the method, a use case with just two areas of expertise - mobility and environment – is presented. The use case focuses on a well-known roundabout intersection in Dejvice (part of Prague 6) called Vítězné Náměstí (Victory square). An architectural design contest (consisting of a complete traffic solution as well) aiming at a complete reconstruction of the public space of and around the Vítězné Náměstí was held. Some conflicting opinions about the winning solution arose Therefore, this is the best choice for our evaluation.

In the case study, the current situation and the winning proposal are compared. There are several changes to the infrastructure. The three main changes would be: changing the roundabout from a two lane roundabout to a turbo-roundabout (the path through the intersection is predetermined), addition of traffic lines (because of four pedestrian crossings around the roundabout) and the tramlines not going through the roundabout but rather around. The Sekyra Group building was added as well as it creates some additional traffic where there is now minimal traffic (except for public transport – Šolínova street – north-west from the roundabout).

For these two case scenarios the same KPIs may be evaluated (Traffic volume, Speed, Fuel consumption, CO_2, PM_X, NO_X and others).

B. Models

The mobility model is based on a microscopic traffic simulation model using software SUMO (Simulation of Urban Mobility) and allows for simulation of both the Traffic and

Environmental impact of the city traffic [13]. SUMO is an open source microscopic simulation tool developed by German Aerospace Center (DLR) that allows for a city infrastructure assessment.

An environmental model developed by the Czech Academy of Sciences that is used in the project is a complex model that includes not only traffic emissions but also particular weather conditions, surface data and additional metrics to calculate how emissions particles move through the environment and how they affect the environment. Mobility modeling can provide more precise data inputs for environmental modeling.

The results from the environmental modeling are not being shown in the outputs below. Only the KPIs from SUMO (mobility modeling) that can be used as inputs for more detailed Environmental modeling. The main difference between SUMO emissions and environmental modeling emissions is that SUMO emissions state the conditions in the exact places where the traffic emissions were created whereas the Environmental modeling emissions state the conditions in other areas when the particles are blown by wind or similar events. This is also the reason why only the SUMO data is being compared in this paper. Until other areas of expertise are included and the project reaches its goal, there is little benefit in including months of work to recalculate and recalibrate the environmental model simply for the purpose of this example of multicriteria evaluation. For the area of one roundabout, the outcomes are expected to be comparable.

The visualization of the traffic microscopic model infrastructure is depicted in the Fig. 4. Most of the geometric changes cannot be seen at this level of detail. The most notable change is in the direction of the tramlines and perhaps the lanes overlaying the roundabout.

C. Data

There are two main types of data used in this modeling. First, it is the data about road geometry of the infrastructure and second, the traffic demand data. The road geometry data come from a public map data and the Institute for regional development (IPR) who provided the public data of the winning proposition. There is no need for precision down to the centimeter, but the roads need to follow approximately the same shape and patterns. Here mostly the traffic rules and traffic organization needs to correspond to reality.

This was achieved both from the public maps, ground surveys and the knowledge of the location. The travel demand data consists of several types of congesting vehicles. Road vehicles (with basic vehicle composition for Prague in 2016 - Cars 86,9 %, Tractor Trailers 12,6 %, Construction veh. 0,1 %, Coaches/BUS 0,4 % [14]), trams and the number of pedestrians at pedestrian crossings were included. To model the traffic flow, origin-destination (OD) matrixes assembled based on a combination of data from the city organization TSK Prague (vehicles per day on each line), data from SmartPlan s. r. o. (traffic flow variations through the day on Jugoslávských partyzánů) and expert assessments of decision making for a chosen direction on the roundabout based on a short-term survey were used. These data-points were transformed into an OD Matrix over a 36-hour period.

Both modeled case scenarios in SUMO are shown in Fig. 5. It is a simplified visualization with only the infrastructure and vehicles being shown. In this scope, the most notable change is that of the tramline modification and the change to a so called turbo roundabout.

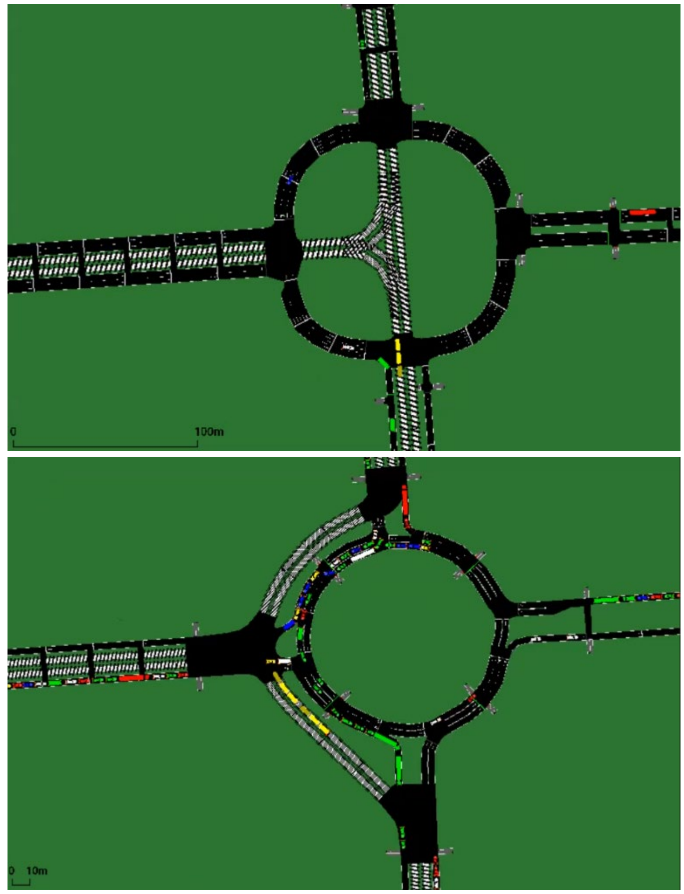

Fig. 5: SUMO model of current (first) and proposed (second) infrastructure.

D. Results

There were some notable surprising results when comparing the KPIs alone. Comparison of the speed and NOx emissions is depicted in Fig. 6. What is surprising about these results is that while one of the scenarios provides better results from the mobility perspective, the other one offers a better scenario from the environmental perspective. This very interesting and it is exactly the reason why these important infrastructural changes need to be evaluated from multiple perspectives. It is also the reason why there need to be thresholds or limits established. While higher values might seem intimidating, without agreeing on certain thresholds that should not be exceeded, one does not really know if this is good or bad for either of these situations. It can also become a dangerous weapon, since only showing colors without a firm decision of the thresholds can be an incomplete, yet frightening, argument that may lead to some poor decisions.

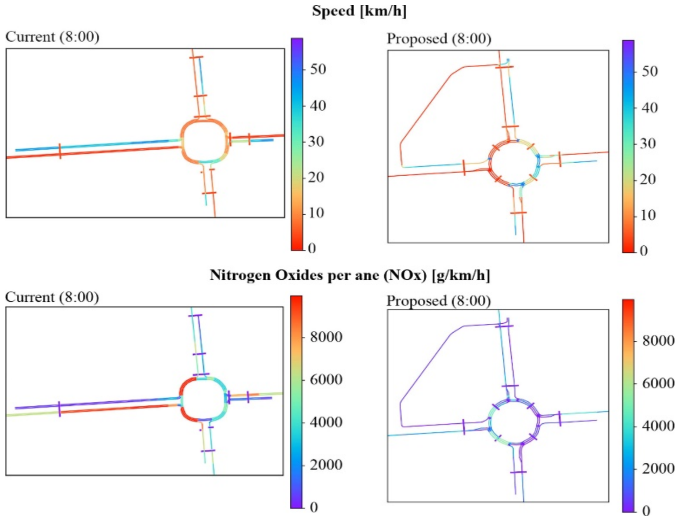

Fig. 6: Heatmaps of Speed and Nitrogen oxides (NOx) at 8:00 a.m., current situation (left) and proposed scenario (right)

Figure 6 shows two different KPIs (speed – km/h and NO_x emissions – g/km/h) for two different case scenarios (current and proposed) all for one particular time interval in the SUMO modelling environment. This figure does not include interpretation of percentages of threshold exceeded as described in the method but rather a simple comparison of the KPIs to further point out the problem.

The hope is to complete this evaluation and include both the entire infrastructure and all areas of expertise by the end of the project to evaluate the operation of the final tool.

Overall, it is concluded that this approach has the potential to become a beneficial tool for public space change evaluation both for the city and the investor.

IV. Conclusions

In this paper, an Interdisciplinary Assessment Method (IAM) for evaluation of scenarios (such as building new infrastructure or influencing the use of electric cars) and their impact on various aspects of life in cities is proposed. It can be used by decision makers to understand the impact of their policies. After defining the different key performance indicators (KPIs) for particular areas (for example transportation or environment as demonstrated in this paper) the proposed changes can be evaluated in a simple way using the proposed smart city equalizer.

In this case, an existing part of infrastructure was assessed comparing current and proposed scenario. Traffic simulation software was used to evaluate KPIs and compare them (using the equalizer to adjust the thresholds). It was demonstrated that this approach works well. In the future, it can include more models, more parameters (KPIs) and can be used on a wider network.

This approach seems to be a viable tool. In the complex environment of a city, it brings the necessary simplification that can help the different stakeholders (decision makers and for example experts from different fields) to see the joint effects of policies. The outcomes are easy to read and compare. The process itself is transparent and easy to understand.

Acknowledgment

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