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Statistical Analysis of the Crosswalk Lighting Design Correctness

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Featured Application: This article is intended for the professionals in the area of roadway lighting, particularly for roadway lighting designers.

Abstract: The main goal of roadway lighting design is ensuring compliance with mandatory lighting standards and thus increasing safety for all road users. On the other hand, a design process being only a part of a road investment has to be completed in possibly a short time, due to business needs. The commonly used method for reconciling both requirements is using predefined lighting projects (templates) which are matched with similar, real-life lighting situations. This approach works well for a typical roadway lighting design but not necessarily for crosswalk illumination due to different specifics of underlying calculations (they focus on the contrast of a pedestrian against its background rather than roadway illumination). As one deals with pedestrian safety here, we decided to perform extensive tests to find out whether a standard compliant lighting project prepared for a given crosswalk can be safely applied (in terms of preserving standard compliance) to another similar crosswalk. To accomplish that, we investigated nearly 900 million situations obtained as modifications of the reference template. Results proved that even a 5% change of layout sizes (crosswalk width, lamp spacing, pole height etc.) makes 40% of obtained projects violate illumination requirements. The conclusion of this result is that the template-based design approach broadly used for roadway lighting cannot be applied for pedestrian crossings as it may cause serious safety issues.

Keywords: roadway lighting; pedestrian safety; lighting design; complexity

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1. Introduction

Roadway lighting standards (CEN 13201:2015 in Europe [1–3], CJJ 45-2015 in China [4], AS/NZS 1158.1.1:2005 in Australia and New Zealand [5], ANSI/IES RP-8-18 in United States [6], ABNT NBR 5101 in Brazil [7], etc.) allow establishing a trade-off between road users comfort and safety, and outdoor lighting system maintenance costs. The latter is determined mainly by an installation's power. Except financial costs, light pollution (caused by over-lighting) has a negative impact on both the environment in terms of greenhouse gas emissions and on human health; thus, a sustainable lighting design is a necessity. Unfortunately, preparation of an optimized lighting project, even for a simple lighting situation, requires considering numerous combinations of input parameters, such as pole height, fixture model/inclination and so on in what leads to complex and multistage calculations. For that reason it is impossible to analyze them all.

Human designers using their intuition and expertise can reduce this huge search space to a reasonably sized set of variants, which are then verified by some industry standard lighting design software such as DIALux or AGi32 [8,9]. It is obvious that such a "guessed" design is not optimal, but the conservative assumptions regarding area size for instance (i.e., intentional oversizing a lighting situation area), guarantee that the final lighting performance meets standard requirements. There are also some promising approaches relying on AI methods [10–12], but they are academic concepts rather than commercially deployed solutions.

The increasing number of accidents occurring at pedestrian crossings resulted in regulations and rules regarding those critical zones. For example see [13] (in Poland) or [14,15] (in Germany). Basically, a typical crosswalk lighting installation consists of two dedicated lamps with asymmetric optics (see Figure 1) and, additionally, the existing or planned road illumination alongside a street.

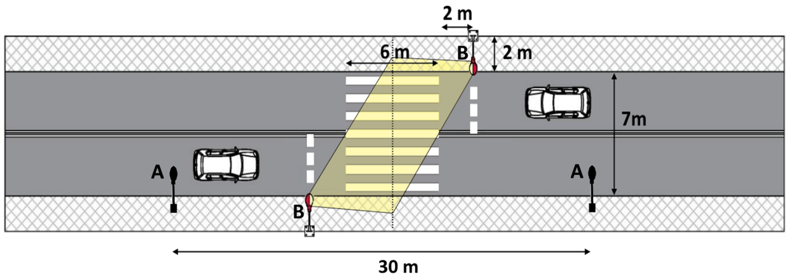


Figure 1. The reference lighting situation in a pedestrian crossing: **A**—streetlights; **B**—dedicated pedestrian crossing luminaires.

Although the aforementioned standards are localized (Poland, Germany), their application reveals the critical problem of applying lighting design methodology used for regular roadways to specific lighting situations, in particular the crosswalks, which are not "compatible" with roads in terms of layout, calculation grids and so forth.

Preliminary analysis of the problem shows that using human intuition and/or expertise may fail; even minor changes of lighting situation properties can cause a standard requirements violation. The example of such a situation is presented in Section 3.

The key considerations are: (i) whether it is an accidental phenomenon or a common issue; (ii) if the latter, how common is it. To answer the above we proceed in three steps:

- Generating a set of test layouts (see Section 4) being modifications of a reference lighting situation. In short, it is achieved by modifying reference parameter values by some percentage.
- Preparing the software checking conformity of particular layouts with the relevant lighting standard.
- Performing a final analysis of the generated data.

2. State of the Art

In this section, we present the technical background of a lighting design, which is necessary for understanding computational problems appearing in this process. A typical implementation of the CEN 13201:2015 standard begins with assigning appropriate lighting classes to particular situations as it is defined in CEN 13201-1:2015 [1]. An assignment schema is based on analyzing a range of factors such as dominant road users (e.g., bicycles, motorized vehicles, pedestrians), allowed speed, presence of parked cars, number of road junctions per kilometer, traffic intensity, etc. It should be emphasized that a municipality which retrofits a lighting installation can impose classes different from those derived from a standard. It may occur in some critical areas such as a neighborhood with a school, a hospital or some other facility with increased risk of an accident or when a given area is the scene of numerous accidents. Once the proper classes are ascribed to all lighting situations, designers select a suitable setup (poles/arms/fixtures/luminous flux dimming) to comply with imposed classes. Those requirements are defined in CEN 13201-2:2015 [2] (see Table 1). Note that finding a well-tailored setup (also in terms of minimized investment costs and the future energy usage) is the most time-consuming part of project preparation. At this point, designers usually apply a generic "template" project covering a set of similar lighting situations. Such a template is not optimized, however, with respect to power usage. Yet another issue accompanying application of such "templates" arises in the case of pedestrian crossings; it leads to violating a lighting standard. Details of the problem are presented later in this paper.

Table 1. M-lighting classes (for traffic routes, dry surface condition) according to the CEN 13201-2 standard [2]: L_{avg}—min., average luminance maintained; U_o—min., overall uniformity; U_l—min. longitudinal uniformity; f_{TI}—max., disability glare; R_{EI}—min., lighting of surroundings.

Class	L_{avg} [cd/m^2] (min. *)	U_o (min.)	U_l (min.)	f_{TI} [%] (max. **)	R_{EI} (min.)
M1	2.00	0.40	0.7	10	0.35
M2	1.50	0.40	0.7	10	0.35
M3	1.00	0.40	0.6	15	0.30
M4	0.75	0.40	0.6	15	0.30
M5	0.50	0.35	0.4	15	0.30
M6	0.30	0.35	0.4	20	0.30

* min.: minimum allowed value; ** max.: maximum allowed value.

2.1. Technical Background: Lighting Design and Performance

Roadway lighting. From the practical point of view, the core action of the roadway lighting design is calculating values of several photometric quantities depending on geometric properties of a situation, light distribution and road reflectance. Those values are computed for all nodes of a rectangular calculation grid covering the road surface and located between two consecutive poles (see Figure 2).

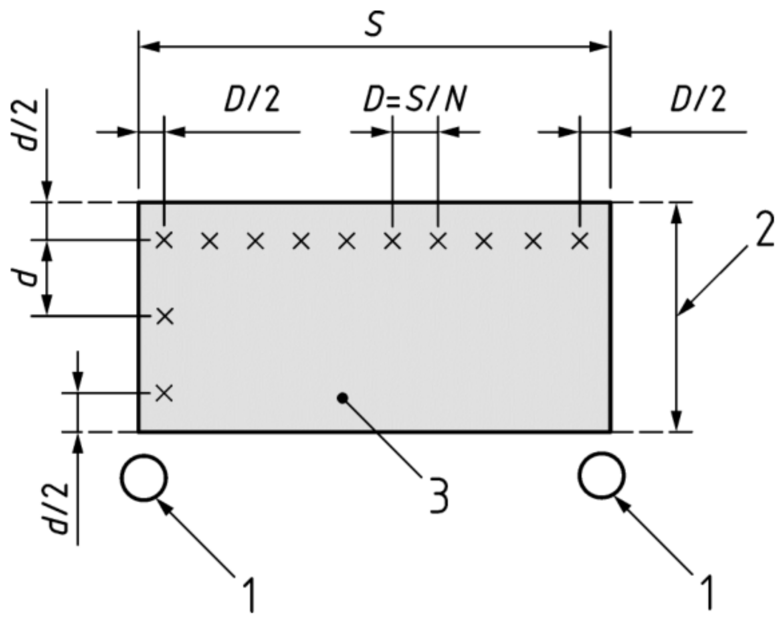


Figure 2. Calculation grid [3]: 1—poles; 2—width of relevant area; 3—field of calculation; S—lamp spacing; d—the spacing between poles in the transverse direction; D—the spacing between poles in the longitudinal direction; N—the number of calculation points in the longitudinal direction.

Since all required photometric quantities are computed, one can verify whether a considered lighting installation performance fulfills lighting standard requirements. Those photometric quantities include:

- L_{avg}—average luminance: refers to luminous flux reflected by the road surface,
- U_o—overall luminance uniformity: the ratio of minimum and average values of L,
- U_l—the minimum maximum value of L, calculated on the points located at a lane axis,
- f_{TI}—threshold increment (disability glare),
- R_{EI}—lighting of surroundings.

Verification of installation performance is accomplished by examining the values of the above parameters against the reference ones. The lighting standard EN 13201-2:2015 for roadways [2] distinguishes six classes enumerated from M1 (highways, expressways) to M6 (local residential streets). Table 1 presents those requirements.

Pedestrian crossing lighting. An inherent element of roadway illumination planning is pedestrian crossing lighting (Figure 1), and as mentioned before, crosswalk illumination is a critical component of public lighting due to the accident risk. There are multiple methods aimed at improving pedestrian safety. Their common goal is to enhance pedestrian visibility. It can be achieved by increasing the contrast, raising a driver's concentration by applying different color temperatures of light in a crosswalk area, setting an "approaching zone" (with increased luminous flux intensity) ahead of a crosswalk or setting a different height for dedicated, pedestrian crossing luminaires.

Another supplementary method of focusing driver attention is embedding LED road markers alongside a pedestrian crossing.

It is worth noting that there is no consensus among experts regarding applying dynamic (adaptive) lighting to crossroads. Blinking or dynamically dimmed lighting may be confusing for a driver (and thus ignored) as similar to the illumination used for road works or as caused by some device failure.

The problem of appropriate crosswalk illumination was considered by [16,17].

For human safety reasons, the lighting must satisfy special qualitative and quantitative requirements, including contrast issues, light color temperature and others (see [18]).

Similarly as for roadways, there are also lighting classes for crosswalks, ranging from PC1 (the most restrictive one) to PC5, respectively. Performance requirements for pedestrian crossings [13] rely on the following photometric quantities:

- $E_{v,\text{avg}}$—average vertical illuminance: refers to a light beam, incident with a vertical plane,
- $U_{o,v}$—overall vertical illuminance uniformity: the ratio of minimum and average values of E_v,
- $E_{h,\text{avg}}$—average horizontal illuminance: refers to a light beam, incident with a horizontal plane,
- $U_{o,h}$—overall vertical illuminance uniformity: the ratio of minimum and average values of E_h,
- $E^{(6)}_{v,\text{min}}$—the minimum value of E_v, calculated for six reference points.

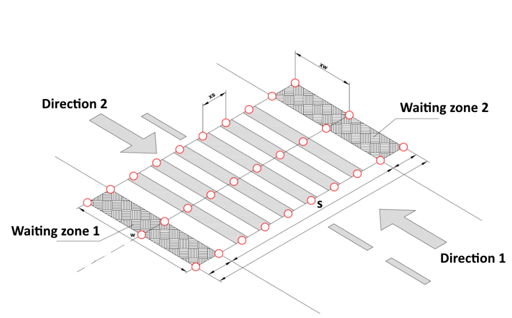
In our considerations, we focus on the PC4 class. Requirements for all PC classes are defined in Table 2:

Table 2. PC-lighting classes for pedestrian crossings, according to the Polish standard [13].

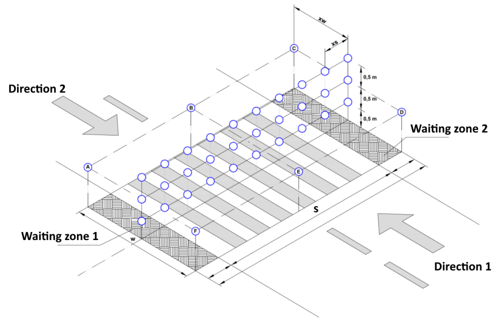
Class	$E_{v,\text{avg}}$ [lx]	$U_{o,v}$	$E_{h,\text{avg}}$ [lx]	$U_{o,h}$	$E^{(6)}_{v,\text{min}}$ [lx]
PC1	75	0.35	75	0.40	5
PC2	50	0.35	50	0.40	4
PC3	35	0.35	35	0.40	4
PC4	25	0.35	25	0.40	3
PC5	15	0.35	15	0.40	2

The feature which distinguishes pedestrian crossing calculations from the roadway ones is that they require three calculation grids (see Figure 3a,b).

Similar to roadway lighting planning, there is a set of layout and installation parameters, which are input variables for photometric computations. It includes road and crossing widths, crosswalk lamp locations and height (not to be confused with signal lights!), crosswalk lamp fixture model and photometric curve. It should be noted that a crosswalk fixture has asymmetric (left or right) optics. Additionally, roadway lighting installation parameters also have to be taken into account, as they affect optical conditions on a crosswalk (e.g., contrast). A number of possible configurations related to an installation (road and crosswalk characteristics are immutable) makes the optimal lighting design searching process infeasible using brute force methods.



(a)



(b)

Figure 3. Calculation grids in pedestrian crossing lighting design: (**a**) horizontal grid for calculating E_h; (**b**) two orthogonal grids for calculating E_v.

2.2. Robust Approach to Roadway Illumination Planning

For many years, lighting designers were only supported by systems, such as DIALux or AGi32 [8,9], verifying correctness of the photometric projects. A project was created relying on the expert's intuition which allowed a designer to match a considered lighting situation to one of the existing patterns/templates. In this approach, lamp spacing 27, 28 or 29 m, for instance, is rounded up (intentionally overestimated) to 30 m. That guarantees meeting standard requirements also in the case of factual distances (27, 28, 29 m); nevertheless. the resultant energy efficiency of this project gets worse, i.e., lighting installation power will be overestimated accordingly. Analogously, other parameters are also rounded up in such a "pessimistic" manner to satisfy the CEN 13201-2 [2] standard requirements. Lighting engineers can overestimate values of other parameters as well, such as road width, pole setback, etc. Thanks to this, multiple similar lighting situations can be covered in a single project. The serious drawback of this approach, however, is reduced energy efficiency implied by the conservative assumptions on road and lighting installation layout.

The second simplification made by designers is going a step further, beyond a simple averaging of a scene geometry. Values of particular geometric parameters are grouped to certain "buckets" with some tolerance. For example, road width is assumed to be 2 m, 3 m, 4 m, etc. Thus one obtains a set of predefined calculation templates which can be widely applied to multiple lighting situations.

The third simplification made by designers concerns lighting classes being assigned to particular roads. The classifications should be made according to the standard CEN/TR 13201-1 [1] which specifies criteria of such an assignment: traffic flow intensity, number of road junctions per kilometer, typical road users and others. In spite of that, designers often omit those criteria and use their intuition and expertise which may affect lighting conditions of roads.

Despite the above simplifications, a typical human-made design process is extremely time-consuming. For example, the retrofit project for 3700 streetlights, made in the city of Cracow, Poland, took seven weeks of a designer's work.

The crucial factor in a lighting project preparation, especially when preparing offers in a tender for public lighting retrofit, is the computation time required for finding an optimal solution. In most cases, *optimal* means implying the lowest power usage (future exploitation costs) and investment outlays. The time overhead is related to the huge search space size. Finding optimal solutions in outdoor lighting design has been the subject to intensive research whose results have been published in multiple works. The research was concentrated in the three main areas: graph-based representations of computational problems [19], application of multi-agent systems [20,21] and distributed processing [22]. In fact, all developed solutions which were successfully applied in real-life large-scale optimization problems have combined the above approaches.

The projects made by an AI system are made quickly, and they are optimal. A calculation for a large-scale optimization (e.g., Tbilisi, Georgia, for 100,000 or Washington D.C., for 54,000 lamps) takes a few hours. Smaller projects take a few minutes. Moreover, resultant installations are not only more effective (from 20% to 30%, in terms of power usage), but also cheaper, what reduces a retrofit cost up to 10%.

3. Robust Approach in Crosswalk Illumination Planning

The majority of outdoor lighting projects are made by designers supported by DIALux-like software solutions based on their intuitive simplifications of particular lighting situations (see Subsection 2.2). This approach, despite of its drawbacks (lower energy efficiency and long design preparation time), guarantees compliance with lighting standards in most cases.

The fundamental question is: can be that approach applied in the case of pedestrian crossing illumination planning?

To find an answer to the above, let us suppose that a crosswalk lighting project will be created according to the template-based methodology described in Subsection 2.2. In this case, an engineer prepares *template-solutions* for several typical road and crosswalk widths (w_r and w_c respectively) and pole heights (h). For values, say: $w_r \in \{4, 5, 6, 7, 8, 9, 10\}$ meters, $w_c \in \{2, 3, 4, 5, 6\}$ meters and $h \in \{4, 5, 6\}$ meters, we obtain 105 potential reference crosswalks. Then, any particular pedestrian crossing is matched to the closest template and a corresponding template-based solution is proposed.

To investigate the effectiveness of the approach for crosswalk lighting design, we tested how the changes made to the lighting situation shown in Figure 1 (without changing lamp settings) affect lighting conditions in terms of compliance with the standard. We used customized software, calculating photometry in accordance with the standard [13].

It was assumed that an installation illuminating the pedestrian crossing of the PC4 class, being in an initial, reference layout (i.e., not modified), fulfills relevant requirements. In the following three scenarios, only one parameter was slightly modified.

Scenario 1. Suppose that a pedestrian crossing and its dedicated lamps are shifted by 3 m relative to roadway lighting luminaires (Figure 4). Note that 3 m is 10% of the actual luminaire spacing.

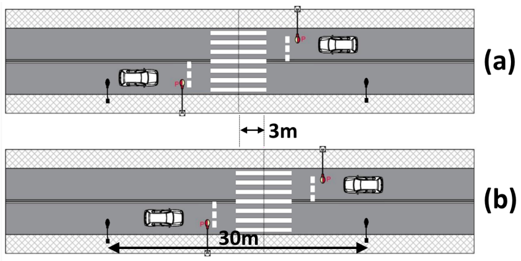


Figure 4. Scenario 1: (**a**) the reference pedestrian crossing, together with dedicated lamps.; (**b**) the crosswalk shifted by 3 m relative to roadway lighting luminaires.

Scenario 2. In the second scenario we increase the road width by 0.7 m (i.e., by 10%), to 7.7 m (Figure 5). Note that a distance of 0.7 m can be roughly compared to the width of two car mirrors.

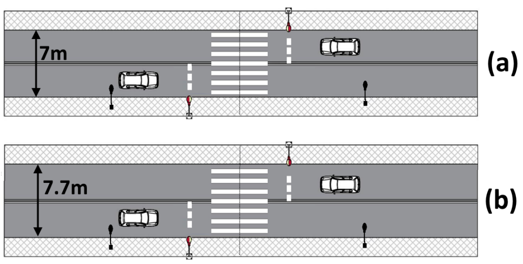


Figure 5. Scenario 2: (**a**) The reference pedestrian crossing. (**b**) Road width increased by 10% relative to (**a**).

Scenario 3. In the third scenario we increase the crossing width by 0.5 m, from 6 to to 6.5 m (Figure 6).

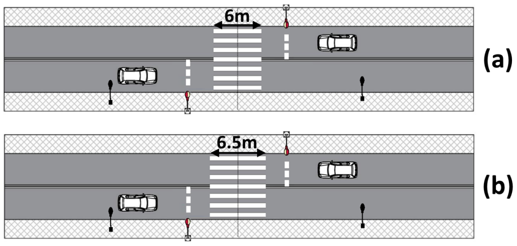


Figure 6. Scenario 3:(**a**) the reference pedestrian crossing; (**b**) crossing width increased by 0.5 m relative to (**a**).

The results obtained for the above scenarios are presented in Table 3.

Table 3. Photometry for modified crosswalk layouts (the PC4 class was assumed). The symbol ✗ denotes violating standard constraints.

	$E_{v,\mathrm{avg}}$ [lx]	$U_{o,v}$	$E_{h,\mathrm{avg}}$ [lx]	$U_{o,h}$	$E^{(6)}_{v,\mathrm{min}}$ [lx]
Scenario 1	24.56 ✗	0.38	60.64	0.45	5.88
Scenario 2	25.96	0.36	58.71	0.38 ✗	6.67
Scenario 3	24.46 ✗	0.43	56.97	0.47	6.30
Reference values	25.00	0.35	25.00	0.40	3.00

The results presented in Table 3 suggest that even minor changes of one parameter can lead to violating standard conformity. It should be noted, however, that in the real-life situations, one deals with at least a combination of the above scenarios. Additionally, variations in streetlight spacings, pole heights and so on can exist. As shown, each individual deviation can influence lighting standard conformity.

4. Massive Compliance Tests: Discussion

Although the above results reveal standard compliance issues for simplified crosswalk lighting, the open question is the scale of the problem. In particular, how those changes interfere: whether they compensate for each other or magnify the effect of nonconformity. To obtain the fully reliable answer, massive tests should be carried out. The results of this investigation are presented in this section.

Testing design compliance sensitivity against crosswalk lighting situation layout distortions is achieved in three steps:

1. Setting a reference layout (e.g., a typical crosswalk) with a set of parameters such as length, width, etc., being subject to deviations and defining allowable variability ranges for particular parameters. Those ranges can be expressed as corrections (in %) of reference values. We reject all distortions which are not acceptable *a priori*, e.g., the crosswalk width equal to 50 m or a pole of the 1 m height.
2. Preparing software checking if a given layout is standard compliant (answer: *yes/no*).
3. Analyzing generated big data consisting of all acceptable layouts. It can be accomplished using an artificial intelligence method (namely, so called *graph grammars*), but these details are beyond the scope of this paper, and they will not be discussed here.

To test the lighting design method robustness, we prepared 898,500,000 layouts based on the initial reference situation shown in Figure 1. Each particular layout was produced by modifying (up to 50% of an initial value, with the step 5%) *at least* one of the following parameters:

- Road width,
- Crosswalk width,
- Lamp spacing,
- Pole setback,
- Row of lamps shifting with respect to the crosswalk,
- Crosswalk lamp position shift $(\delta x, \delta y)$; it was assumed that locations of those lamps are axially symmetric with respect to the crosswalk center.

Note that neither fixture power nor photometric solid is subject to modifications. It is because once a fixture setup was selected (for the reference situation) we only verify whether it also complies with lighting standard requirements for a geometrically modified scene.

To show how the standard conformity depends on distortion (Δ) magnitude, we probed a ratio of non-compliant solutions for consecutive distortion values. For example, a distortion $\Delta = 35\%$ denotes that neither value change applied to the parameters listed above, and it exceeds 35% of a reference value.

Figure 7 presents the obtained results for Δ ranging from 5% to 50%, with the step 5%.

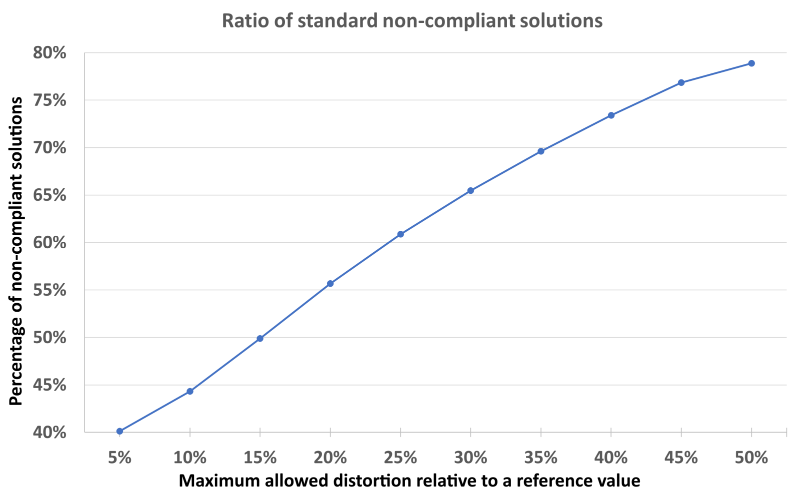


Figure 7. The ratios of standard non-compliant solutions for various distortions. The 0% distortion denotes $\Delta < 5\%$.

As can be seen on the above chart, even the slight modifications of the basic layout yield a very high 40% rejection rate; $\Delta = 15\%$ impacts nearly the half of the designs.

5. Conclusions

As it was shown in the previous section, even a 5% change of a parameter value yields a 40% risk of changing the final status of a crosswalk lighting project from *standard compliant* to *not compliant*. For that reason, it is not possible to rely on a human designer's intuition and/or expertise, as shown in the case of typical standards for roadway lighting (e.g., [3]). The layout simplification approach, applied for typical roads (which have a property of the translation symmetry) fails for structurally complex lighting situations such as crosswalks, and it cannot be used for them.

Moreover, it is necessary to implement specialized tools for crosswalk lighting design, other than existing software which lacks the support for such tasks [8,9].

Fortunately, a number of potential combinations for simple situations (as reference one, shown in Figure 1) is limited enough to apply a brute-force verification which has substantially lower computational time complexity compared to an optimization, i.e., finding a standard compliant lighting setup. The crucial task for the software development industry is to provide appropriate tools capable of performing bulk, scalable (in terms of a number of parameters and lighting situations) operations such as testing all potentially applicable optics, pole heights, etc., against compliance with a given lighting standard.

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