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Urban single-lane roundabouts: A new analytical approach using multi-criteria and simultaneous multi-objective optimization of geometry design, efficiency and safety

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A B S T R A C T

Building safe and effective roundabouts requires optimizing traffic (operational) efficiency (TE) and traffic safety (TS) while taking into account geometric factors, traffic characteristics and local constraints. Most existing simulation-based optimization models do not simultaneously optimize all these factors. To capture the relationship among geometry, efficiency and safety, we put forward a model formulation in this paper. We present a new multi-criteria and simultaneous multi-objective optimization (MOO) model approach to optimize geometry, TE and TS of urban unsignalized single-lane roundabouts. To the best of our knowledge, this is the first model that uses the multi-criteria decision-making method known as analytic hierarchy process to evaluate and rank traffic parameters and geometric elements of urban single-lane roundabouts. The model was built based on comprehensive review of the research literature and existing roundabout simulation software, a field survey of 61 civil and traffic expert engineers in Croatia, and field studies of roundabouts in the Croatian capital city of Zagreb. We started from the basis of Kimber's capacity model, HCM2010 serviceability model, and Maycock and Hall's accident prediction model, which we extended by adding sensitivity analysis and powerful MOO procedures of the bounded objective function method and interactive optimization. Preliminary validation of the model was achieved by identifying the optimal and most robust of three geometric alternatives (V.1-V.3) for an unsignalized single-lane roundabout in Zagreb, Croatia. The geometric parameters in variant V.1 had significantly higher values than in the existing design V.0, while approaches 1 and 3 in variant V.2 were enlarged as much as possible within allowed spatial limits and Croatian guidelines, reflecting their higher traffic demand. Sensitivity analysis indicated that variant V.2 showed the overall highest TE and TS across the entire range of traffic flow demand and pedestrian crossing flow demand at approaches. At the same time, the number of predicted traffic accidents was similar for all three variants, although it was lowest overall for V.2. The similarity in predicted accident frequency for the three variants suggests that V.2 provides the greatest safety within the predefined constraints and parameter ranges explored in our study. These preliminary results suggest that the proposed model can optimize geometry, TE and TS of urban single-lane roundabouts.

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1. Introduction

Numerous models for determining roundabout capacity under mixed-traffic conditions suggest that it is strongly affected by geometric elements (Dahl and Lee, 2012). Studies of roundabouts in various countries, particularly of single-lane roundabouts (signaled and unsignaled) in urban areas, have shown that proper design and modeling can significantly improve traffic (operational) efficiency (TE) (Al-Madani, 2003; Easa and Mehmood, 2006; Ma et al., 2013; Vasconcelos et al., 2013; Mauro and Cattani, 2012), as well as traffic safety (TS) (Mandavilli et al., 2009; Kim and Choi, 2013; Søren, 2013). On the other hand, these and other studies (Mauro, 2010; Montella et al., 2013; Yap et al., 2013) have highlighted that existing design and modeling standards are not always adequate for cases when there is a need for simultaneous optimization of geometry, TE and TS. Methods for predicting traffic accidents have been described based on geometric elements (Maycock and Hall, 1984), sight distance (Zirkel et al., 2013), as well as traffic dynamics and the behavior of drivers as they pass through the "potential conflict" zone of the intersection (Mauro and Cattani, 2004).

Studies of roundabout TE, conducted primarily in Western Europe and Australia, have led to several computational mathematical models that have been integrated into various roundabout software engineering simulation tools (e.g. ARCADY, SIDRA, and PTV VISSIM). These mathematical models can be classified as (1) empirical, (2) gap acceptance, and (3) microsimulation. Each category has its disadvantages (Yap et al., 2013). Generally countries with updated roundabout design guidelines apply Highway Capacity Manual models from 2000 or, in some cases, 2010 for analyzing roundabout capacity (Chodur, 2005; Tanyel et al., 2007). These models take into account empirical and/or gap-acceptance models, but they do not address the level of service (LOS) or TS, nor do they simultaneously optimize capacity and geometry parameters. The capacity formulation for urban single-lane roundabouts developed in HCM is based on the mathematical formulation of geometry parameters developed by Kimber (1980) (Robinson and Rodegerts, 2000) and formulation of queue length developed by Wu (2001). Differences among these models in how data are collected and analyzed, as well as deviations between predicted and actual driver behavior, make it difficult to identify the most suitable ones for given conditions (Mauro, 2010; Montella et al., 2013). Planners and designers should be aware of the specific limitations of these models and the selected model(s) must be calibrated against field data or other validated models to ensure accuracy. Unfortunately this calibration step is often neglected (Gagnon et al., 2009; Qin et al., 2011). In situations where the model is not even developed and the ideal model is in doubt, it may be advisable to analyze roundabout TE using various approaches, and HCM models may be the most appropriate for such work (Mauro, 2010). In addition, none of these models exploits advances in traffic accident prediction, or in sensitivity analysis, which can help identify which alternatives are more robust to traffic flow perturbations.

Multi-criteria decision making (MCDM) involves optimizing one or several objective functions, where the objective refers to the system condition under consideration, over a defined set of solutions corresponding to the various alternatives available. MCDM methods are the approaches most frequently used to guide decision making in transport sciences; three examples include the preference ranking organization method for enrichment evaluation (PROMETHEE), analytic hierarchy process (AHP), "*višekriterijumsko kompromisno rangiranje*" (VIKOR), and the technique for order preference by similarity to ideal solution (TOPSIS) (Chen et al., 2014; Podvezko and Sivilevičius, 2013). In road transport, the AHP method has been applied most often to decisions related to planning and investing in transport infrastructure (Wang et al., 2014). A recent review of the AHP literature (Barić et al., 2016) indicates that although the method has been applied to nearly all types of transport problems, few studies have used it to quantify how much certain geometric elements of roundabouts affect TE and TS parameters, which would allow optimization of those elements during design and modeling.

Multi-objective optimization (MOO) approaches are already well established and widely used in engineering (Marler and Arora, 2004), particularly in heuristic solution approaches which are now widespread in civil and traffic engineering. In road transport, the MOO procedure has been applied most often in highway construction and alignment (Yang et al., 2014), as well as to solve dynamic traffic routing problems in congested freeway networks (Cong et al., 2013). MOO and genetic algorithms have also been applied to analysis of traffic flows. Vlahogianni et al. (2005) described a multilayered structural optimization strategy that can help capture the spatiotemporal characteristics of traffic flow as well as identify the most appropriate neural network structure for doing so. Several studies have also applied MOO to roundabouts. Al-Masaeid (1999) developed a logit model to optimize geometric design and traffic flow dynamics, while other authors have focused on maximizing speed consistency, TS and TE (Easa and Mehmood, 2006; Rubio-Martín et al., 2015). Quddus and Washington (2015) developed a new weight-based, map-matching genetic algorithm for calculating the shortest path and vehicle trajectory. While this literature makes clear that MOO can be effective for modeling geometry and traffic flow of roundabouts, it remains unclear whether and how MOO can be used to simultaneously optimize various geometry, TE and TS parameters.

Croatia has approximately 200 roundabouts, of which more than 60% lie within or on the edge of urban areas, and many of them deviate substantially from international standards for roundabout planning, design and modeling, which compromises their TE and TS (Legac et al., 2008). The country has no tradition of systematically monitoring capacity and other key performance indicators of roundabouts, though the government has called for the building and reconstruction of roundabouts as part of its National Traffic Safety Plan 2011–2020 (Pilko, 2014). The most recent national guidelines stipulate where urban and suburban single-lane roundabouts should be built, what geometry they should have, and how capacity should be calculated (Deluka-Tibljaš et al., 2014). However, the guidelines do not indicate what models or simulation soft-