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An Optimization Model for Highway Work Zones Considering Safety, Mobility, and Project Cost

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Abstract: Highway Work Zones (HWZs) are associated with significant adverse impacts on safety, mobility, and work costs. The objective of this paper is two-fold: First, to quantify the impacts of HWZs on safety, mobility, and work costs. Second, to develop an optimization model to minimize the total costs associated with HWZs by controlling site geometry, Temporary Traffic Control (TTC), and work management. This model implements a location-based schedule within the cost evaluation. A genetic algorithm is used to determine a set of optimal scheduling and decision variables. The performance of the model is demonstrated in a case study. The results reveal that crash costs, which were often ignored or only included indirectly in previous works, are a substantial cost component. Their explicit inclusion in the optimization process significantly affects the total cost and the optimal operations of the HWZ. Furthermore, the inclusion of a location-based schedule in the model is instrumental and affects the optimal solution since all HWZ cost components are affected by the work processes and project duration. Moreover, consideration of the effects of TTC on the optimized function has a substantial influence on the total cost. The model can support transportation agencies and local authorities in mitigating the adverse impacts associated with HWZs.

Keywords: Highway Work Zones; traffic safety; traffic mobility; location-based scheduling; optimization

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1. Introduction

Highway Work Zones (HWZs) are categorized as 3R projects: Rehabilitation, Resurfacing, and Restoration [1]. They are needed to deal with aging roads whose safety and functionality deteriorate with time and to improve road capacity to meet increasing travel demands. However, HWZs are associated with significant adverse impacts on safety, mobility, and work costs.

In safety, the literature shows that HWZs increase the risk of traffic crashes (e.g., [2–4]). There were 39,000 injuries and 842 fatalities in U.S. HWZs in 2019 [5]. Moreover, in contrast to the general trend, HWZ fatalities have not decreased over the years [6]. Furthermore, these figures may not show the full magnitude of safety impacts caused by HWZs since crashes at HWZs tend to be underreported [7,8]. A state-of-the-art review [9] on work zone safety showed that 18 out of 21 articles found that work zones increase crash rates, and 14 out of 27 articles found that work zones increase crash severity. In mobility and the associated externalities, HWZs account for approximately 10% of congestion and 24% of nonrecurring delays on U.S. highways [10]. They also have negative environmental, economic, and social impacts, including increased vehicle emissions and fuel consumption [11]. HWZ delays have been shown to lead to aggression towards road workers, such as throwing objects or threatening traffic controllers [12]. Finally, HWZs are associated with substantial costs: In 2014, their annual cost in the US was around 19 billion dollars [13].

Many factors influence the safety, mobility, and work costs associated with HWZs. These can be allocated into three categories: (1) Site geometric design, such as lane width and work zone length; (2) Work management, such as the number and timing of work hours; and (3) Temporary Traffic Control (TTC) measures, such as the use of Dynamic Speed Displays (DSDs) or presence of flaggers. A detailed description of the design and operations of HWZs and TTC is provided in [14]. These factors often have conflicting effects on safety, mobility, and work costs. For example, working at night often reduces traffic delays, but increases work costs and crash risks. Therefore, there is a need for a cost model that can jointly consider safety, mobility, and work costs and support their minimization.

The literature on quantification of HWZ costs (e.g., [15–17]) commonly considers six cost components: work costs are captured by agency and TTC costs; mobility related costs are captured by the monetary value of lost time, Vehicle Operation Costs (VOC), and emission costs; and safety impacts are captured by crash costs.

Several studies have developed HWZ optimization models that consider at least some of these cost components. Table 1 summarizes these studies in terms of the cost components and decision variables that they incorporate. Some developed a single objective model to minimize project cost, and others developed multi objective models. For example, [18] built a Pareto front that captures the trade-off between agency cost and the combined cost of delays and crashes. Several other studies developed models to find the Pareto front of the trade-off between safety and mobility costs [19] or between work and mobility costs [20,21]. All studies in Table 1 considered a simple agency cost and schedule, aside from a recent study [22] that considered detailed agency cost and scheduling by developing a multi-objective optimization model to minimize construction cost and duration based on the number of equipment and their optimal allocation.

The current HWZ optimization models shown in Table 1 commonly account for the agency and lost time costs. The other cost components, namely TTC, VOC, emissions, and crash costs, are either ignored or considered as a proportion of the agency or lost time costs. None of the reviewed models accounted for all six cost components. Furthermore, agency costs are generally estimated using coarse assumptions of constant work rates and set-up time and costs, which do not account for the project schedule and its cost implications. The treatment of crash rates and their costs is also lacking. Crash rates are commonly derived from traffic delays, ignoring the effect of the site geometry, TTCs used, work schedule and management, and past crash records on the specific road section. Travel speeds and road capacities are generally assumed constant. VOC was assumed to depend only on lost time, regardless of the traffic conditions. TTC costs were assumed constant per day and do not account for the quantity and TTC type used. Emission costs were ignored in all these models.

Table 1. Summary of HWZs' optimization models.

	Decision Variables		Cost Components Considered					
Study	**Site Geometry**	**Work Management**	**Agency**	**TTC**	**Lost Time**	**VOC**	**Crash**	**Objective**
Amândio et al. (2021) [22]	-	Equipment used	X					Multi
Abdelmohsen and El-Rayes (2016) [20]	Workspace length, lateral clearance, shoulder use, access and egress method	Time of work	X	X	X			Multi
Du and Chien (2014) [23]	Workspace length, shoulder use	Time of work	X		X		X	Single
Chien and Tang (2014) [15]	Workspace length	Time of work, idling time, crew composition	X		X	X	X	Single
Meng and Weng (2013) [24]	Workspace length	Time of work		X	X		X	Single
Kandil et al. (2010) [18]	Workspace length	Time of work	X		X		X	Multi
Yang et al. (2009) [25]	Workspace length, layout configuration	Time of work, crew composition	X		X		X	Single
Tang and Chien (2008) [26]	Workspace length	Time of work, idling time, crew composition	X		X	X	X	Single
Chen et al. (2005) [27]	Workspace length, layout configuration	Time of work, idling time	X		X		X	Single
Chen and Schonfeld (2005) [28]	Workspace length, layout configuration	-	X		X		X	Single
Chen and Schonfeld (2004) [29]	Workspace length	Time of work, idling time, cycle duration	X		X		X	Single
Jiang and Adeli (2003) [21]	Workspace length	Time of work	X	X	X		X	Multi
Chien et al. (2002) [30]	Workspace length	Time of work, idling time, cycle duration	X		X			Single
Chien and Schonfeld (2001) [31]	Workspace length	-	X		X		X	Single
Schonfeld and Chien (1999) [32]	Workspace length	Cycle duration	X		X			Single
Mccoy and Mennenga (1998) [16]	Workspace length	-		X	X	X	X	Single
Fwa et al. (1998) [33]	-	Time of work, idling time			X			Single
Martinelli and Xu (1996) [34]	Workspace length, layout configuration	-		X	X	X	X	Single

Few of the models listed in the table accounted for the effects of diverted traffic. Those that did [27,28] assumed external diversion fractions that do not explicitly depend on the delays caused by the HWZ during different periods of the day. The decision variables used in the models are limited to general characteristics that affect the agency and lost time costs, such as the workspace length or the work duration and timing. Variables related to the implementation of TTC on safety costs are not considered.

To overcome these gaps in current models, the following enhancements are proposed in this research: The developed model considers all six cost components. A location-based schedule is incorporated in the optimization process to predict agency costs and the project duration more accurately. This affects all six cost components. A crash cost model based on the Empirical Bayes (EB) method is used. This model considers crash severity and depends on the road geometry, TTC, and construction management decision variables. Travel delay, VOC, emission, and crash costs are modeled as dependent on the road type and geometry, as well as road traffic demand and flow states. Traffic diversions to alternative routes are also accounted for in the model. Finally, TTC decision variables' effect on crash rates and TTC cost is incorporated. The rest of this paper is organized as follows: The next section presents the overall optimization model and the estimation of its cost components. Application of the optimization model to an HWZ case study and its results are presented in the following sections. Finally, discussion and conclusions are presented.

2. Methods

2.1. Objective Function

The optimization model is designed to minimize the total HWZ cost, including all six components that were discussed above. Decision variables related to all site geometric design, TTC, and work management are set in the optimization. Table 2 presents the decision variables considered and their influence on the various cost components, both directly and indirectly. The information on the effects of the decision variables on crash rates and on travel speeds are derived from the reviews in [19,35]. The cost components within the objective function are defined in terms of the additional cost caused by the HWZ presence compared to those of normal operations of the road section. Therefore, the values of some cost components may be negative. The overall optimization model is given by:

$$Min(TPC) = Min(AGC + TTC + LTS + VOC + EMC + CRC) \tag{1}$$

$$s.t.$$

$$LB_i \leq X_i \leq UB_i \qquad i = 1, 2, \ldots, n \tag{2}$$

$$AGC + TTC \leq B^{max} \tag{3}$$

$$D \leq D^{max} \tag{4}$$

$$TCMF \leq TCMF^{max} \tag{5}$$

$$LT \leq LT^{max} \tag{6}$$

$$G(X) \leq 0 \tag{7}$$

where, TPC is the total project cost. AGC is the agency cost. TTC is the temporary traffic control cost. LTC is the lost time cost. VOC is the vehicle operating cost. EMC is the emission cost. CRC is the crash cost. X is the array of decision variables. X_i is the value of decision variable i. LB_i and UB_i are the lower and upper bounds on the decision variable. D is the project duration. D^{max} and B^{max} are the maximum allowed project duration and available budget, respectively. $TCMF$ is the total crash modification factor. $TCMF^{max}$ is the maximum acceptable value of this variable. LT is the lost time. LT^{max} is the maximum acceptable lost time. $G(X)$ are functions of the decision variables that define additional constraints, such as technical constraints or constraints on the geometric design of the HWZ.

2.2. Agency Cost

Agency cost is the direct project cost, which includes material, equipment, wages, and site overheads. As noted above, the previous studies listed in Table 1 used coarse estimates of the hourly work rates and setup times, often ignoring the composition of tasks and their schedule within the project. However, tasks within the projects can be undertaken in several alternative ways (e.g., variations in equipment, number of workers, or crews), which lead to different project costs and work rates.

A location-based work schedule, which determines daily working hours for equipment and personnel including night work, is used within the model. Thus, it captures the effect of crew composition and the daily number of working hours on the agency cost. The schedule considers the working hours needed to complete the various tasks, setup times, and time lags among tasks. The decision variables that define the work schedule also affect other cost components through the project duration that they dictate. Finally, in some cases, the shoulders are used as temporary travel lanes [20,21]. The cost of their preparation for travel is also included. The agency cost is given by:

$$MC = \sum_j MQ_j \cdot MUC_j \tag{8}$$

$$EC = \sum_d \sum_j EWH_{j,d} \cdot EHC_j \cdot \left(1 + ENF_{j,d} \cdot ENAC\right) \tag{9}$$

$$WC = \sum_d \sum_j WWH_{j,d} \cdot WHC_j \cdot \left(1 + WNF_{j,d} \cdot WNAC\right) \tag{10}$$

$$AGC = MC + EC + WC + SC + IC \cdot D \tag{11}$$

where, MC, EC, and WC are the material, equipment, and workers' wage costs, respectively. SC is the cost of preparing the shoulders as a travel lane. The index j signifies the working tasks within the project. MQ_j and MUC_j are the material quantity used in the task and its unit cost, respectively. The index d signifies working days from the start of the work and for its entire duration. $EWH_{j,d}$ and $WWH_{j,d}$ are the number of working hours for equipment and workers, respectively. EHC_j and WHC_j are the corresponding hourly equipment costs and wages, respectively. $ENF_{j,d}$ and $WNF_{j,d}$ are the fractions of nighttime hours for equipment and workers, respectively. $ENAC$ and $WNAC$ are the corresponding additional cost of night work for equipment and workers. IC is the daily indirect cost.

Table 2. Decision variables' influence on the cost components.

Category	Decision Variables	Affected Costs	Cost Components Affected by the Decision Variables				
			Agency	TTC	Lost Time	VOC and Emissions	Crash
Geometry	Lane width	Affects crash rates and Free Flow Speed (FFS) and, through that, crash, lost time, vehicle operation, and emission costs.			X	X	X
	Shoulder width	Affects crash rates and FFS and, through that, crash, lost time, vehicle operation, and emission cost. It also affects agency costs to prepare shoulders as temporary traffic lane.	X		X	X	X
	Lateral clearance	Affects crash rates and FFS and, through that, crash, lost time, vehicle operation, and emission costs.			X	X	X
	Workspace length	Determines project duration that affects all cost components.	X	X	X	X	X
TTC	Posted speed limit	Affects crash rates and FFS and, through that, crash, lost time, vehicle operation, and emission costs.			X	X	X
	PCMs (Portable Changeable Message Signs)	Affects crash rates and, through that, crash cost. It also requires additional TTC cost.		X			X
	TMAs						
	Police patrol						
	Flagger presence						
	Speed display						
Work management	Time of work	Affects crash rates and project duration and, through that, crash, lost time, vehicle operation, and emission costs.			X	X	X
	Crew composition	Determines project duration that affects all cost components.	X	X	X	X	X
	Working days in the week	Affects amount of exposed traffic flow to HWZ presence and, through that, crash, lost time, vehicle operation, and emission costs.			X	X	X

2.3. Temporary Traffic Control Cost

The TTC cost component extends the model presented in [20]. TTC cost includes the cost of using temporary traffic control devices and wages for police patrols and flaggers. These costs have largely been ignored or only implicitly included as part of the agency costs. The TTC equipment cost depends on the length of the work zone, which dictates the quantity of equipment needed. The length of the work zone area that is separated with TTC from the travel lanes includes the workspace and a constant length composed of tappers and buffers. The workspace length is a decision variable in the model. Nighttime work increases both equipment and personnel TTC costs with the need for additional lighting equipment and the higher wages paid. The TTC cost is given by:

$$ETTC = [INSC + RENC + RELC + REMC + OTTC] \cdot (1 + NF_d \cdot TENAC) \tag{12}$$

$$WTTC = \sum_{d} WH_d[PHC + FHC]\cdot(1 + NF_d\cdot TWNAC) \tag{13}$$

$$TTC = ETCC + WTCC \tag{14}$$

where, $ETTC$ and $WTTC$ are TTC equipment costs and personnel wages, respectively. L_d^{wz} is the workspace length on day d. $L1$ is the length from the start of the shoulder taper until the end of the downstream taper, excluding the workspace. $RENC$ is the TTC daily rental cost. $RELC$ is the cost of relocating the TTC from one day to the next. $INSC$ and $REMC$ are the installation and removal costs for a distance unit, respectively. $OTTC$ is the cost of optional TTC (e.g., VMS, DSD). WH_d are the number of working hours on day d. PHC and FHC are police and flagger hourly wages, respectively. NF_d is the fraction of nighttime work on day d. $TENAC$ and $TWNAC$ are the corresponding nighttime additional costs for TTC equipment and wages, respectively.

2.4. Lost Time Cost

Increased travel times through HWZs are caused by reduced travel speeds due to changes in the road geometry and the delays at queues that form because of reduced traffic capacity in the HWZ bottleneck. These delays may cause a fraction of the travel flow to divert to alternative routes [36], which reduces the delays on the HWZ route and increases travel times on the alternative routes. Most current models ignore the effects of diversions on the HWZ costs. The few studies that accounted for it, e.g., [27,28], assumed a constant diversion rate that does not depend on traffic conditions. This model explicitly captures diversion effects.

In this model, the traffic delay through the HWZ is separated into queue delay at the approach to the HWZ and increased travel time within the HWZ itself due to reduced speeds. This separation supports better estimation of vehicle operating and emissions costs that depends on speed and differs during queuing periods. The queue delay is caused when the flow approaching the HWZ exceeds its entry capacity. A deterministic quasi-dynamic point queue model is implemented to capture this delay. Each working day is divided into time slices. The sequence of queues at the end of the intervals is calculated by:

$$QL_{t,d} = max\left\{0,\ QL_{t-1,d} + \left(Q_{t,d}^{up} - C_{t,d}\right)\cdot T\right\} \tag{15}$$

where the index t signifies a time interval. $QL_{t,d}$ is the queue length on the point at the upstream end of the work zone at the end of interval t on day d. $Q_{t,d}^{up}$ is the demand traffic flow in the upstream section approaching the bottleneck at the HWZ entrance point. T is the time length of the interval. $C_{t,d}$ is the entry capacity to the section, which is calculated using procedures described in [37].

$$C_{t,d} = NOL\cdot BC\cdot F_{t,d}^{hv}\cdot F_{t,d}^{drv}\cdot F_{t,d}^{wa}\cdot F_{t,d}^{lcs}\cdot F_{t,d}^{rain}\cdot F_{t,d}^{lght}\cdot F_{t,d}^{int} \tag{16}$$

where NOL is the number of open lanes in the section. BC is a base capacity per lane. $F_{t,d}^{hv}$, $F_{t,d}^{drv}$, $F_{t,d}^{wa}$, $F_{t,d}^{lcs}$, $F_{t,d}^{rain}$, $F_{t,d}^{lght}$, and $F_{t,d}^{int}$ are adjustment factors for heavy vehicles, driver population, work activity, side of lane closure, rain, light condition, and nonadditive interaction effects that capture correlation among the adjustment factors, respectively.

The total delay to vehicles in the queue waiting to enter the HWZ section during the interval is given by:

$$QD_{t,d} = \begin{cases} \frac{1}{2}(QL_{t,d} + QL_{t-1,d})\cdot T & QL_{t,d} > 0 \\ \frac{(QL_{t-1,d})^2}{2\left(C_{t,d} - Q_{t,d}^{up}\right)} T & QL_{t,d} = 0 \end{cases} \tag{17}$$

where $QD_{t,d}$ is the queueing delay in interval t to all vehicles.

The total queue lost time in the entire project (QLT) is the summation of all queues caused by the HWZ:

$$QLT = \sum_{d} \sum_{t} QD_{t,d} \tag{18}$$

The relevant time intervals may extend beyond the end of the workday because queues may still take time to dissipate. Reduced speeds within the HWZ result from changes in the free flow speed (FFS) and section capacity. This study implements the FHWA method to calculate FFS in the HWZ as a function of its geometric design [35]:

$$FFS_{t,d} = BFFS - F^{lw}_{t,d} - F^{lc}_{t,d} - F^{m}_{t,d} - F^{a}_{t,d} \tag{19}$$

where $BFFS$ is the base FFS which is based on the posted speed limit. $F^{lw}_{t,d}$, $F^{lc}_{t,d}$, $F^{m}_{t,d}$, and $F^{a}_{t,d}$ are adjustment factors for lane width, lateral clearance, median type, and access points, respectively.

The prevailing travel time in the HWZ section is estimated based on the flow entering the section and using a flow-delay function. It is assumed that the entry capacity to the HWZ, which is defined by Equation (16), regulates traffic flow and ensures under-saturated conditions. Thus, the flow that can enter the section during a time interval is given by:

$$Q_{t,d} = min\left\{C_{t,d}, \ \frac{QL_{t-1,d}}{T} + Q^{up}_{t,d}\right\} \tag{20}$$

In the implementation, the travel times for vehicles within the HWZ section (and, through them, also travel speeds) are estimated with the Bureau of Public Roads (BPR) function:

$$TT_{t,d} = \frac{\left(L^{wz}_{d} + L1\right)}{FFS_{t,d}} \left(1 + \alpha\left(\frac{Q_{t,d}}{C_{t,d}}\right)^{\beta}\right) = \frac{\left(L^{wz}_{d} + L1\right)}{V_{t,d}} \tag{21}$$

where $TT_{t,d}$ is the travel time in the HWZ section. L^{wz}_{d} is the workspace length at day d. $L1$ is the length of HWZ tappers and buffers. α and β are parameters. $V_{t,d}$ is the travel speed. The values 0.15 and 4, respectively, are used in the case study.

Travel speeds that would prevail if an HWZ was not implemented are also calculated. The reduced travel speed lost time ($RSLT$) captures the difference in travel time with the HWZ compared to without it. $RSLT$ is the summation of all reduced travel speeds' delay caused by the HWZ:

$$RSLT = \sum_{d} \sum_{t} \left(\frac{\left(L^{wz}_{d} + L1\right)}{V_{t,d}} - \frac{\left(L^{wz}_{d} + L1\right)}{V^{norm}_{t,d}}\right) \cdot Q_{t,d} \tag{22}$$

where $V^{norm}_{t,d}$ is the normal travel speed in the section with no work.

The additional travel time through the HWZ may cause some travelers to bypass it by changing their routes. Diverted vehicles will experience the travel times on the alternative routes. They may also increase the travel times and queue delays to vehicles that were using these roads already, before the HWZ implementation. A route choice model is used to estimate the vehicle flows on the routes through the HWZ and alternative routes:

$$Q^{up}_{t,d} = \left(\frac{1}{1 + exp\left[\theta \cdot \left(RT^{WZ}_{t,d} - RT^{alt}_{t,d}\right)\right]}\right) \cdot TD_{t,d} \tag{23}$$

$$Q^{alt}_{t,d} = \left(1 - \frac{1}{1 + exp\left[\theta \cdot \left(RT^{WZ}_{t,d} - RT^{AL}_{t,d}\right)\right]}\right) \cdot TD_{t,d} \tag{24}$$

where $Q^{up}_{t,d}$ and $Q^{alt}_{t,d}$ are the vehicle demand that chooses the HWZ and the alternative routes at interval t and day d, respectively. $TD_{t,d}$ is the total demand for travel that may use the HWZ section. θ is a parameter. $RT_{t,d}^{WZ}$ and $RT_{t,d}^{alt}$ are travel times on the two routes. The alternative route may be an aggregation of multiple routes. In the implementation, its travel time is assumed to be constant. However, increased section travel times and queue delays could be calculated in a way similar to that of the ones through the HWZ.

The calculation of the route flows and travel times is iterative. Given travel times on the two routes, route flows are calculated using Equations (23) and (24). The flow demands that arrive to the HWZ section ($Q_{t,d}^{up}$) are used to calculate updated section travel times and queue delays through the HWZ and the alternative route. The travel times and route flows are updated, and the process is repeated until convergence is reached.

The total lost time in the system is the summation of all queue delays and reduced speed delays for all vehicles. Its cost is obtained by multiplying it by a vehicle-type specific hourly rate, whose estimate is based on [17]:

$$LT = QLT + RLST \tag{25}$$

$$LTC = LT \cdot \sum_{y} F_y \cdot HC_y^{LT} \tag{26}$$

where LT is the lost time. The index y signifies the vehicle type (passenger cars, single-unit trucks, and combination trucks). F_y is the fraction of the total traffic of vehicle type y. HC_y^{LT} is the hourly cost rate of lost time.

2.5. Vehicle Operating Cost

VOC is associated with fuel and engine oil consumption, tire wear, repair and maintenance, and mileage-related depreciation. HWZs affect VOC through the changes in speeds and queue delays that they generate. The NCHRP Report 133 method [17] assumes that the additional VOC consists of three terms: Reduced speed VOC that captures the cost of decelerating to the HWZ's speed and accelerating back to the upstream speed. Stopping VOC captures the cost to vehicles forced to stop to join a queue. Idling VOC captures the effects of the time spent in a queue. The VOC cost is given by:

$$RVOC = \sum_{d}\sum_{t}\sum_{y} Q_{t,d} \cdot \left[\left(RUC_y \left(V_{t,d}^{norm} \right) - RUC_y(v_{t,d}) \right) \cdot F_y \right] \tag{27}$$

$$SVOC = \sum_{d}\sum_{t}\sum_{y} \left(Q_{t,d}^{up} \right) \cdot SUC_y \left(V_{t,d}^{norm} \right) \cdot F_y \tag{28}$$

$$IVOC = \sum_{d}\sum_{t}\sum_{y} QD_{t,d} \cdot IUC_y \cdot F_y \tag{29}$$

$$VOC = RVOC + SVOC + IVOC \tag{30}$$

where $RVOC$, $SVOC$, and $IVOC$ are the VOC of reduced speed, stopping, and idling time, respectively. RUC_y, SUC_y, and IUC_y are vehicle unit VOC for reduced speeds, stopping, and idling time, respectively.

2.6. Emission Cost

Vehicles emit several pollutants that cause numerous health damages. The model calculates emission rates as a function of the travel speed. The HWZ emission cost is defined by the difference between the costs of the conditions with and without the HWZ. The emission cost is separated into two parts: The change in emission rates caused by the reduced speeds within the HWZ, and the change caused by stop and go conditions in a queue at the HWZ entry point. Travel speeds and queue lengths are derived from the traffic flow model described above. The Cal-B/C model [17] defines emission rates for travelled distance unit. The distance vehicles travel within the queue is determined by the number of vehicles in the queue and assumes they are evenly split among the available lanes. The emission cost is given by:

$$REMC = \sum_d \sum_t Q_{t,d} \cdot (L_d^{wz} + L1) \cdot \sum_y \sum_k PC_k \left[\left(ER_{y,k}(v_{t,d}) - ER_{y,k}\left(V_{t,d}^{norm}\right) \right) \cdot F_y \right] \tag{31}$$

$$IEMC = \sum_d \sum_t Q_{t,d} \cdot \left(\frac{Q_{t,d} \cdot VL}{2N} \right) \cdot \sum_y \sum_k PC_k \left[\left(ER_{y,k}\left(V_{t,d}^{ID}\right) - ER_{y,k}\left(V_{t,d}^{norm}\right) \right) \cdot F_y \right] \tag{32}$$

$$EMC = REMC + IEMC \tag{33}$$

where $REMC$ and $IEMC$ are the emission cost of reduced speed and idling time, respectively. $ER_{y,k}$ is the emission rate per distance travel unit of pollutant k for vehicle type y. PC_k is the health damage cost of a unit of pollutant k. VL is an average vehicle length. $V_{t,d}^{ID}$ is travel speeds in the queue. N is the number of available lanes.

2.7. Crash Cost

The model uses the Empirical Bayes (EB) method to estimate expected crash rates for the road section before the HWZ implementation. It uses Safety Performance Functions (SPFs) and actual crash records on the specific section to estimate expected crash rates with different severities. It is assumed that the area affected by the HWZ is from the start of the advanced warning area to the end of the downstream transition area. The EB crash rates are given by:

$$ECR_s^{noWZ} = \left[W_s \cdot SPF_s + (1 - W_s) \cdot \frac{CR_s}{Y} \right] \cdot (L_d^{wz} + L2) \tag{34}$$

$$W_s = \frac{U}{U + Y \cdot SPF_s} \tag{35}$$

where the index s signifies the crash severity. ECR_s^{noWZ} is the expected yearly number of crashes without HWZ implementation per kilometer. W_s is the SPF weight in the EB estimate. $L2$ is the length of the area affected by the HWZ, excluding the work area itself. Y is the number of years for counting crashes at the site. CR_s is the rate per kilometer of crashes of severity s observed at the site over Y years. U is an estimate of the uncertainty of the SPF model.

Crash Modification Factors (CMFs) are then applied to the expected crash rates to estimate their change due to HWZ implementation. They capture the individual effects of factors such as lane and shoulder width, presence of police patrols and flaggers, time of work, travel speed, lateral clearance, PCMs, DSD, and Truck Mounted Attenuators (TMAs). Their compound impact is calculated by the Total Crash Modification Factor ($TCMF$). This research implements the Highway Safety Manual [38] method to calculate $TCMF$. The expected number of crashes on a road section depends on traffic flow through it. Thus, traffic diversion to alternative routes affects numbers of crashes both on the HWZ route and the alternatives:

$$TCMF = \prod_m CMF_{m,s} \tag{36}$$

$$CRC = \left(\frac{\sum_d \sum_t Q_{t,d}}{365 \cdot AADT} \right) \cdot TCMF \cdot \sum_s ECR_s^{noWZ} \cdot CC_s \tag{37}$$

where the index m signifies the countermeasure. $CMF_{m,s}$ is the crash modification factor of countermeasure m for crash severity s. CC_s are the crash costs. AADT is the annual average daily traffic.

2.8. Solution Evaluation Procedure

The procedure to evaluate the objective function for a candidate solution, which includes site geometry, TTC, and work management decision variables, is presented in Figure 1. First, a project schedule is built for this solution considering the characteristics of the project, including bill of quantities, project tasks, time lag among project tasks, available crew formations, project total length, and duration constraints. The output of the project schedule determines the project duration, time of work, workspace length, number of working hours for each task, and the fraction of night work for each task. This information is used to calculate the agency and TTC costs. The project schedule is also used as input to the traffic flow model, together with information on traffic flows through the HWZ and alternative routes.

Delays at HWZs may cause diversion of traffic flows to the alternative routes. A route choice model is used to estimate these flows using the travel times on the two routes. The traffic flow model estimates capacities and FFSs, travel times, speeds, and queue delays for the HWZ and alternative routes for each time period and day of work. The new flows are used to re-estimate speeds, delays, and travel times. The iterative process is repeated until convergence is obtained. The final travel times and delays are used in calculating lost time, vehicle operation, and emission costs. It is also used, together with crash records for the HWZ, to calculate crash costs. Finally, the total HWZ cost is the summation of the six cost components. The optimization is conducted using a genetic algorithm [39]. Several GA parameters were tested to achieve the minimal cost. The values that yielded the best results were population size 200, number of generations 300, and crossover and mutation rates 0.8 and 0.01, respectively.

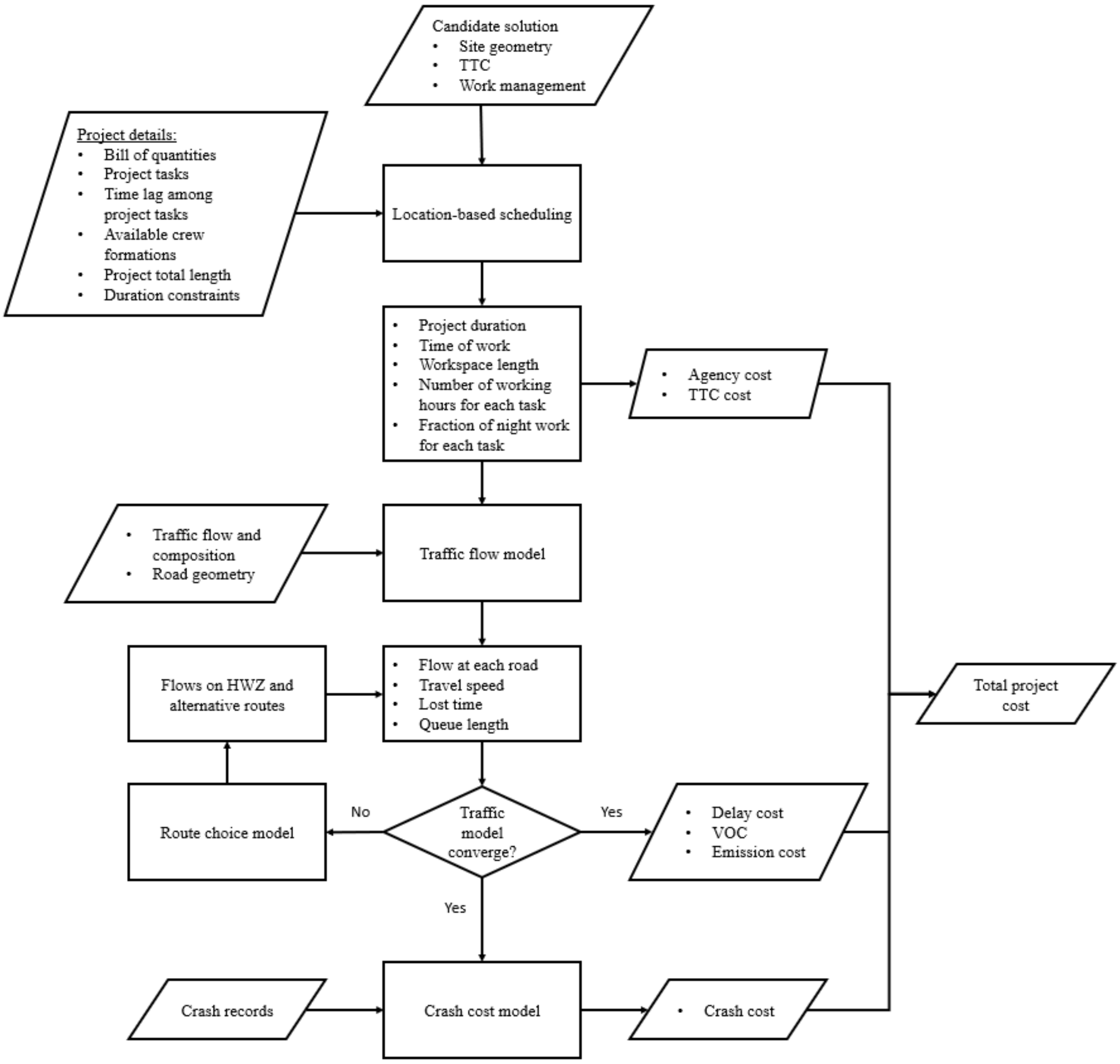

Figure 1. Objective function evaluation procedure.

3. Case Study

The application of the optimization model is demonstrated in a resurfacing project on the right lane of one direction of a four-lane divided highway. Inputs and characteristics are summarized in Table 3. The SPF suitable for this project is [40]:

$$SPF_s = e^{10.4071} * AADT^{-2.811} * e^{I_s} * AADT^{0.1703 * ln(AADT)} \tag{38}$$

$I_s = \{-2.3926, -1.4845, 0\}$ are of crash severity coefficients for fatal, serious, and slight crashes, respectively. The estimate of the uncertainty of this SPF model is 1.3984.

All CMFs are from [19], except those related to TMAs, which are based on [41]. The total resurfaced area is 72,000 (m^2). The project is composed of three tasks: (1) grinding the old asphalt layer, (2) cleaning and applying the tack coating layer, and (3) pouring a new asphalt layer. Each of these tasks may be accomplished with different crew compositions, which are shown in Table 4. In total, there are four possible crew compositions made up of the combinations of the task alternatives. The time lag between consecutive tasks is 30 min. HWZ set up and removal times are 3 h. Project daily indirect costs (IC) are 500 ($).

In addition to this base scenario, two experiments are conducted, as shown in Table 5. In Experiment 1, four different scenarios are solved that are defined by combinations of two types of constraints on the project: the possibility of nighttime work (7PM-5AM) and the availability for use of optional TTC (PCM, DSD, TMA, police, and flagger). In Experiment 2, the scenarios differ in the way cost components are calculated. The base case is the same as in Experiment 1. The other scenarios reflect simplified models that are commonly used in the literature for the various components. The simplified agency cost scenario as in [23,26] replaces the location-based model with one based on average values and workspace length. With this model, the agency cost and work duration are given by:

$$AGC = \sum_d Z^1 + Z^2 \cdot L_d^{wz} \tag{39}$$

$$D = Z^3 + Z^4 \cdot L_d^{wz} \tag{40}$$

where Z^1 is a fixed setup cost. Z^2 is an average agency cost per kilometer. Z^3 is the setup time, and Z^4 is the additional time required per work zone kilometer. The values assumed for these parameters are $0,\ 36{,}000\ \left(\frac{\$}{\text{km}}\right),\ 3\ (\text{hr}),\ \text{and}\ 8\ (\text{hr})$, respectively.

The simplified crash costs model, as in [25,27], assumes that crash rates depend only on lost time, as calculated in Equation (41):

$$CRC = CR \cdot ACC \cdot LT \tag{41}$$

where CR is the crash rate. ACC is the average crash cost. The values assumed for these parameters are 40 $\left(\frac{crashes}{100M\ veh-hr}\right)$ and 287,400 $\left(\frac{\$}{crash}\right)$, respectively.

In the alternative route scenario, it was assumed that vehicles that reroute to bypass the HWZ experience a delay of 20 min.

Table 3. Case study input and characteristics.

Variable	Value	Source
	Road geometry	
Project total length	20 (km)	
Original lanes' width	3.6 (m)	
Original shoulder's width	1.8 (m)	
Work zone area L1	620 (m)	FHWA (2009) [14]
Work zone area L2	1070 (m)	
	Traffic model and lost time costs	
Rain	No	
Base capacity and capacity adjustment factors		Al-Kaisy and Hall (2003) [37]
Base FFS and FFS adjustment factors		FHWA (2017b) [35]
Heavy vehicle percentage	3%	
AADT on one carriageway	35,000 (veh/day)	
Daily and hourly traffic count		Road section in Israel
Passenger cars' monetary value of travel time	21.89 ($/veh-hr)	FHWA (2017a) [17]
Heavy vehicles' monetary value of travel time	23.06 ($/veh-hr)	
Alternative route additional travel time	20 (min)	
	Crash data and costs	
Fatal crash cost	9,100,000 ($)	FHWA (2018) [42]
Injury crash cost	955,500 ($)	
Slight crash cost	27,300 ($)	
Fatal crash record	1 (crash/km-4y)	
Injury crash record	2 (crash/km-4y)	
Slight crash record	7 (crash/km-4y)	
	TTC costs	
Renting TTC	621 ($/km-day)	Abdelmohsen and El-Rayes (2016) [20]
Installing TTC	621 ($/km)	
Relocating TTC	621 ($/km-day)	
Removing TTC	621 ($/km)	
PCMS rental cost	700 ($/month)	
TMA rental cost	150 ($/month)	HercRentals [43]
Police patrol wage	30 ($/hour)	PayScale (2020) [44]
Flagger wage	12 ($/hour)	
Work at night increase TTC cost	15%	
Shoulder preparation for traffic fixed cost	5000 ($)	Abdelmohsen and El-Rayes (2016) [20]
Shoulder preparation for traffic variable cost	3105 ($/one foot width-km)	
	VOC and emission costs	
Vehicle unit VOC	NCHRP Report 133 method	FHWA (2017a) [17]
Emission rates and health damage cost	Cal-B/C model	

Table 4. Alternatives for project tasks.

Task	Alternative for Task	Work Rate (m^2/hour)	Material Quantity (m^2)	Material Cost ($/$m^2$)	Equipment Cost ($/$m^2$)	Wage Cost ($/hour)
1	1	667	0	0	325	175
	2	600	0	0	300	175
2	1	833	72,000	0.7	150	105
3	1	683	72,000	5	325	245
	2	708	72,000	5	367	280

Table 5. Case study experiments.

Scenario	Nighttime Work	Optional TTC	Cost Components
A (base)	Allowed	Available	Proposed model
		Experiment 1	
1B	Allowed	Not available	Proposed model
1C	Not allowed	Available	Proposed model
1D	Not allowed	Not available	Proposed model
		Experiment 2	
2B	Allowed	Available	Simplified agency cost
2C	Allowed	Available	Simplified crash cost
2D	Allowed	Available	Ignore alternative route

4. Results

The results of Experiment 1 are presented in Table 6 and costs are presented in US dollars. In the base scenario (A), the total cost is 668,690, which mostly consists of agency costs (92%). The costs increase by about 6% in scenario 1B, which does not use optional TTC measures. In this scenario, crashes contribute 4% of the project cost compared to −4% in the base scenario. Thus, the additional cost of the optional TTC measured is justified by the crash cost's savings. Except for the removal of TTCs, the solution remains similar, and so are the costs of the various components. In scenarios 1C and 1D, nighttime work is not permitted. This constraint almost triples the total cost and drastically changes its composition. As work in these scenarios shifted to daytime hours with high traffic flow, the weight of lost time costs increased from 4% in the base scenario to 64% and 61%, respectively. Agency costs now represent only 35% and 33% of the total cost, respectively.

VOC and emission costs were low in all scenarios. The negative costs shown in some scenarios for emissions and crash costs signify a decrease in the cost compared to normal operations without a HWZ. Reductions in emission costs mostly occur in situations where there are speed reductions due to the HWZ, but substantial queues are not accumulated. For crash rates, in addition to lower speeds, the use of TTCs is the main source of lower crash rates in scenarios A and 1C. Thus, the results show that the cost of TTC implementations is justified by their safety cost benefits, which are not negligible.

The site geometry and optimal crew compositions were similar in all scenarios. The lane and shoulder widths are at the maximum values that do not require preparing the left shoulder for travel and the high associated costs. Increasing the lateral clearance at the expense of the left lane, which affects both safety and speeds, was also not justified. The number of daily working hours was 13 h in the base scenario, but only 11 h in all other scenarios. The longer working hours in scenario A were made optimal by the combination of nighttime work and the use of optional TTCs that reduced the lost time and crash costs for longer periods of the day. This allowed a project duration of 14 days in scenario A, compared to 18 days in the other scenarios.

The results of Experiment 2 are presented in Table 7. Scenario 2B assumes that the agency costs depend solely on the project length, ignoring the effect of crew composition and the number of daily working hours. Compared to the base scenario (A), the noticeable difference in this solution is that the daily working hours are reduced, leading to a longer project duration. The longer project duration does not affect agency costs, and so the optimal solution focuses on reducing the lost time by decreasing working hours during higher traffic hours. Scenario 2C calculates crash costs as a function of lost time. This means that the implementation of TTC measures is assumed to increase costs but does not affect crash costs. Therefore, they were not used in the optimal solution. Effects of any other geometric or management variables on crash rates or severity are also not captured. Nighttime work involved relatively little lost time, and so the associated crash costs are very small. Scenario 2D accounts for the additional costs associated with route diversions. The results of the base scenario are that most work takes place during the nighttime. Therefore, only a small fraction chooses to re-route and the results do not differ substantially from those of the base case.

In all scenarios that allowed the use of optional TTC measures, PCMs, police patrol, and TMA were included in the optimal solution. Flagger presence and DSD were excluded, due to their low impact on crashes. It should also be noted that the use of *TCMF* (Equation (36)) means that the marginal effect of a TTC decreases in the presence of other effects.

Table 6. Experiment 1 results.

	Scenario A	**Scenario 1B**	**Scenario 1C**	**Scenario 1D**
Costs				
Total project cost ($)	668,690	709,540	1,825,400	1,928,300
Agency	91.92%	89.06%	34.60%	32.76%
TTC	7.62%	6.42%	2.72%	2.05%
Lost time	3.59%	0.59%	64.14%	61.40%
Vehicle operation	0.67%	0.29%	1.32%	1.35%
Emission	−0.03%	−0.03	0.07%	0.06%
Crash	−3.76%	3.67%	−2.86%	2.38%
Project impacts				
Total delay (veh-hr)	1094	192	53,400	53,997
TCMF	0.27	2.04	0.24	1.65
Workspace length (m/day)	1418	1103	1103	1103
Project duration (days)	14	18	18	18
Decision variables				
Site geometry				
Lane width (m)	3.3	3.3	3.3	3.3
Left shoulder width (m)	1.8	1.8	1.8	1.8
Lateral clearance (m)	0.3	0.3	0.3	0.3
TTC				
Posted speed limit	90	90	90	80
PCMs	Yes	-	Yes	-
Police patrol	Yes	-	Yes	-
Flagger presence	-	-	-	-
Speed display	-	-	-	-
TMA	Yes	-	Yes	-
Work management				
Work start time	10 PM	11 PM	5 AM	5 AM
Number of working hours	13	11	11	11
Tasks crew compositions	Alt. 1-1-1	Alt. 1-1-1	Alt. 1-1-1	Alt. 1-1-1

Table 7. Experiment 2 results.

	Scenario A	**Scenario 2B**	**Scenario 2C**	**Scenario 2D**
Costs				
Total project cost ($)	668,690	766,560	681,440	664,630
Agency	91.92%	93.93%	91.31%	93.62%
TTC	7.62%	7.66%	6.50%	8.10%
Lost time	3.59%	0.58%	1.78%	1.20%
Vehicle operation	0.67%	0.30%	0.43%	0.39%%
Emission	−0.03%	−0.03%	−0.03%	−0.04%
Crash	−3.76%	−2.44%	0.01%	−3.27%
Project impacts				
Total delay (veh-hr)	1094	204	555	365
TCMF	0.27	0.27	-	0.27
Workspace length (m/day)	1418	1000	1260	1260
Project duration (days)	14	20	16	16
Decision variables				
Site geometry				
Lane width (m)	3.3	3.3	3.3	3.3
Left shoulder width (m)	1.8	1.8	1.8	1.8
Lateral clearance (m)	0.3	0.3	0.3	0.3
TTC				
Posted speed limit	90	90	90	90
PCMs	Yes	Yes	-	Yes
Police patrol	Yes	Yes	-	Yes
Flagger presence	-	-	-	-
Speed display	-	-	-	-
TMA	Yes	Yes	-	Yes
Work management				
Work start time	10 PM	11 PM	10 PM	10 PM
Number of working hours	13	11	12	12
Tasks crew compositions	Alt. 1-1-1	Alt. 1-1-1	Alt. 1-1-1	Alt. 1-1-1

5. Discussion and Conclusions

This paper presents an HWZ optimization model that quantifies the impact of HWZs on safety, mobility, and work costs. The effect on safety is captured by the TCMF of the HWZ compared to before HWZs' implementation. The effect on mobility is captured by the total traffic delay in terms of vehicle-hours and changes in traffic speeds caused by the HWZs. Afterwards, the effect on safety and mobility are monetized and added to the work costs to obtain the total HWZ cost that is minimized by the developed model. Constraints on specific cost components, such as maximum allowed delays or minimum desired safety levels, were not considered in the case study. However, the model can support the addition of such constraints imposed by transportation agencies or local authorities (e.g., police department, local municipality).

The main results of the case study are as follows: unlike what previous HWZ optimization models (Table 1) showed, crash costs have a substantial effect on project cost and HWZ operations. Therefore, the additional costs associated with improving TTC measures were justified by the cost savings derived from crash reductions. It should also be noted that the case study was for dual carriageway roads, which generally experience lower crash rates compared to single carriageway roads. Thus, the importance of crash costs may be even more pronounced in these types of roads. The use of location-based scheduling of the work improves the reliability of the cost estimates since it captures the effects of the daily working hours and crew formation on work progress rate. This relation is ignored in current models. Incorporating a diversion traffic model showed the substantial difference of the diverted fractions to alternative roads between different times of work, thus highly affecting the project's total cost and decision variables. Finally, considering TTC's effects on safety had a major effect on crash costs and, therefore, the total cost.

The case study also showed that, among the various cost components, the changes in emission costs were very small in all cases. VOCs are a considerable cost component only when substantial queues form. The other costs vary substantially under different constraints, such as nighttime work. The case study assumed that the impact of the HWZ is limited to the working hours. In many cases, the layout changes due to HWZ projects are present during the entire day. The effects on traffic flow and safety during these times were not considered. The results suggest that road agencies should use detailed models that incorporate crash and lost time costs to mitigate these costs. The models should also use detailed project scheduling to improve their precision and better plan HWZ operations. Furthermore, TTCs have substantial effects on project cost and, therefore, guidelines on using TTCs at HWZs should be updated to increase their usage.

The impact of HWZs on mobility and safety was captured by Equations (26) and (37), respectively, and then monetized using Equations (27) and (38), respectively, to be added to the total optimization model in Equation (1). The developed model shows the effect of HWZ on safety and mobility; however, its objective was to find the minimal total cost. Therefore, future work is focused on capturing the trade-offs among the HWZ's effect on safety, mobility, and work costs by developing a multi-objective optimization model to further investigate the current knowledge on mitigating the adverse impacts of HWZs.

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