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Automatic Drawbridge Scheduling by Integrating Highway and Waterway Traffic Flow Information

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Abstract:
As inland waterway usage intensifies, it increasingly intersects and conflicts with railway and road transportation modes, highlighting the need for efficient management of these critical junctures. In particular, movable bridges represent a key intersection of highway and waterway traffic but also a potential source of conflict. This paper proposes and analyzes the use of automatic schedulers that consider both highway and waterway traffic, reduce conflicts, and make key decisions about bridge use. The METANET macroscopic traffic model is elaborated to allow the simulation of drawbridge openings on the highway mainline, based on the modelling of mainstream metering. Several MPC-based schedulers are proposed using the designed highway traffic model and key vessel information, aiming to study the impact of the bridge opening and scheduling on highway traffic. The simulation results indicate a significant reduction in traffic conflicts at drawbridge intersections due to the implementation of these schedulers. The functioning of the schedulers is shown to be robust and demonstrate verifiable behavior, indicating their high potential in real-world applications.

1. INTRODUCTION

Highway drawbridges are key pieces of infrastructure of two modes of transport: road and waterborne traffic. Inland shipping of goods is currently being promoted by the European Commission as a way of improving environmental friendliness and safety as well as of reducing road congestion (Segovia et al. (2022b)). However, the resulting increase in vessel traffic on inland waterways will inevitably lead to an increase in required drawbridge openings, causing congestion on affected highways, an example of which can be seen in Figure 1. Highway congestion greatly increases traffic emissions and entails economic damage (Frejo and Camacho (2012)). At the same time, vessels carry important goods and long waiting times for drawbridges elevate shipping costs. For instance, the Rhine-Alpine corridor's throughput represents 19% of the EU GDP whilst passing through some of its most densely populated areas and most important economic centers (Segovia et al. (2023)). Delays in both vessel traffic and on-land economic activity surrounding the Rhine's drawbridges therefore have detrimental impacts on the EU's economy. In this situation, whether to open a drawbridge or allow vehicle traffic to remain flowing freely therefore presents a dilemma to drawbridge schedulers, as well as a conflict of interest.

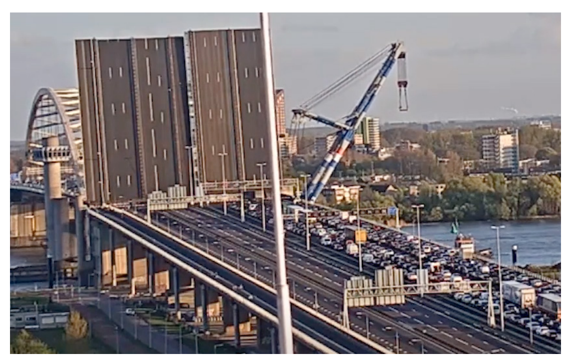

Fig. 1. A view of the congested Brienenoordbridge in the Netherlands as a vessel passes (nu.nl (2017))

Automatic solutions to this problem remain scant. Drawbridge openings are currently scheduled either at the signalled arrival of a vessel (as for Connecticut (2023)) or at set times (as for Rijkswaterstaat (2023)) without considering actual traffic levels of either highway or waterway. Automatic scheduling of drawbridge openings could therefore reduce negative effects of openings on both vehicular and vessel traffic by considering both modes of traffic simultaneously. It furthermore has the potential to reduce the need for expensive new infrastructure works such as tunnels and tall suspension bridges by making better use of existing drawbridge infrastructure.

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Extensive work has been realized on traffic flow modelling and scheduling. For highway networks, it is often realized through macroscopic traffic models such as METANET (Papageorgiou et al. (2010)). For waterway networks, macroscopic traffic flow modelling has not been researched to the same extent, although some models exist (e.g. Yip (2013)), and microscopic models are more often used because of the importance of individual ship characteristics on waterway flow (Qi et al. (2021)). Scheduling of waterway traffic has been realized more extensively, through the scheduling of locks and drawbridges for multiple vessels traveling down a single waterway or network of waterways (Segovia et al. (2023)). Segovia et al. (2022a) and Segovia et al. (2022b) all present different approaches for scheduling locks and drawbridges along a waterway. A study by Dehghani et al. (1993) studies the economic costs of both vessel and vehicle delays due to bridge openings. These costs were however determined in the context of urban road traffic, with a queue model as for traffic lights used. The direct interaction of highway and waterway traffic and the effects they can have on each other have therefore not been extensively studied.

This paper presents the design of an automatic scheduler that considers both highway and waterway traffic flow. For this purpose, a novel method of macroscopically modelling the impact of opening a highway drawbridge for highway traffic using METANET is proposed. The models used to simulate both highway and waterway traffic, as well as the method with which a drawbridge opening is modelled in these traffic flow models is considered in section 2. Section 3 then presents the design of the automatic drawbridge scheduler considering both highway and waterway traffic. Section 4 evaluates the functioning of the scheduler and its tunable parameters through numerical results. Conclusions and future work are outlined in section 5.

2. DRAWBRIDGE OPERATION

2.1 Macroscopic Traffic Flow Modelling

Traffic flow modelling can be pursued through a multitude of methods broadly divided into three categories: (i) microscopic, describing the behavior of individual cars, (ii) mesoscopic, describing vehicles in aggregate terms yet implementing behavioral rules for individual cars, and (iii) macroscopic, describing traffic as a continuum flow (van Wageningen-Kessels et al. (2015)). In this paper a macroscopic model is chosen for its suitability in real-time control. The METANET traffic flow model is chosen, a second-order macroscopic model, that is able to accurately represent the capacity drop (Yuan et al. (2015)). This model is modified to simulate traffic dynamics on a freeway with a drawbridge located on its mainline.

In the METANET traffic flow model the variables vehicular density ($\rho_i(k)$), space-mean speed ($v_i(k)$) and traffic outflow ($q_i(k)$) are calculated for each highway segment i and for every time $t = kT$ in hours, where T is the time step used for simulation. These, along with a set of boundary conditions that determine traffic behavior at edge cases such as the highway inflow, outflow, on-ramp, and various traffic control measures are calculated as in Hegyi et al. (2005) and may be consulted there.

2.2 Drawbridge Opening

To the best of our knowledge, the inclusion of drawbridge openings has not been previously integrated into the METANET traffic model. Indeed, there is very limited literature about the effects of a drawbridge opening on highway traffic flow in general. Therefore, the existing traffic control method, 'mainstream metering' is adapted to approach the effect of a drawbridge opening on highway traffic flow. This adaptation is based on the similarity between the effects of mainstream metering, which temporarily halts traffic flow by including traffic lights on the mainline of the freeway, and those of a drawbridge opening, which similarly interrupts the entire traffic flow for a set period.

Mainstream metering is modelled as a simple reduction in the outflow q_i of the segment i in which it is implemented:

$$q_i(k) = \min(r_b(k)C_m, q_{o,i}(k)), \tag{1}$$

where $q_{o,i}$ is the outflow of the segment that would occur without metering, C_m the capacity of the mainstream and $r_b \in \{0, 1\}$ the mainstream metering rate. If the flow is reduced by the mainstream metering (i.e. $q_i(k) < q_{o,i}(k)$) the velocity needs to be updated accordingly:

$$v_i(k) = \begin{cases} v_{o,i}(k)\dfrac{q_i(k)}{q_{o,i}(k)} & \text{if} \quad q_i(k) < q_{o,i}(k) \\ v_{o,i}(k) & \text{otherwise} \end{cases}, \tag{2}$$

where $v_{o,i}$ is the velocity that would occur without mainstream metering.

In order to represent a drawbridge opening, r_b is set to 0 for the time that traffic has to stop whilst the drawbridge is open for τ_b, i.e.

$$r_b = \begin{cases} 0 & \text{if} \quad k_b \leq k < k_b + \tau_b \\ 1 & \text{otherwise} \end{cases}, \tag{3}$$

where k_b is the time step at which the drawbridge opens and τ_b the time length of the drawbridge opening. During a drawbridge opening, τ_b is considered to be sufficiently long to allow all vehicles to clear, allow all waiting vessels to pass and physically open and close the drawbridge.

Simulation issues arise due to the abrupt and large interruption of traffic flow caused by the drawbridge opening with this method. These issues are counteracted by two further refinements of the METANET model, as suggested by Papageorgiou (1998) and Hegyi et al. (2005). The first issue is that congestion can grow to force traffic to a standstill in downstream segments due to the sudden capacity drop of the drawbridge segment as densities approach ρ_{max}. This can result in the model producing negative velocities and therefore flows in the downstream segments. A negative velocity is an unrealistic scenario for highway traffic, amounting to vehicles driving backwards. These values are therefore manually set to 0 whenever v or q are calculated to be less than 0. According to Papageorgiou (1998), "there is no evident practical reason" for not manually guaranteeing positive or zero flow and velocity, as density will be calculated accordingly and vehicle continuity is thereby ensured.

The sudden capacity drop of the highway in itself presents another issue. The flow and speed of vehicles on the highway drops sharply after the drawbridge opens and is quick to recover after the drawbridge has closed. In general, it is assumed that the anticipation constant ν is constant for normal traffic flow, that is to say congestion builds up and dissipates at the same rate. However, the authors in Yuan et al. (2015) have shown that congestion dissipates more slowly than it builds up as drivers accelerate more carefully after congestion. A high and low value for ν is therefore added to the current model to better represent the extreme congestion around the drawbridge, i.e. (Hegyi et al. (2005)):

$$\nu_i = \begin{cases} \nu_{high} & \text{if } \rho_i(k+1) > \rho_i(k) \\ \nu_{low} & \text{otherwise} \end{cases} . \tag{4}$$

2.3 Inland Vessel Traffic Flow Modelling

The number of macroscopic vessel traffic flow models is limited. Furthermore, within the same time scale a vastly larger number of vehicles than vessels will cross a highway drawbridge. Modelling a continuous vessel flow is therefore not practical. Instead, the key parameters needed to investigate the effect of vessels arriving at the drawbridge are generated randomly and associated with each vessel x (Segovia et al. (2022a)). These are:

- N_x, the number of vessels x on the waterway for which the drawbridge needs to open,
- $W_x(k)$, the waiting time of each vessel x at the drawbridge at time step k,
- $A_{x,e}$, the desired (most fuel efficient) arrival time of each vessel x,
- $A_{x,f}$, the fastest possible arrival time for each vessel x, sailing at maximum velocity.

Here, $x \in X_{all}$ is used as the index for vessels on the waterway. The terms $A_{x,e}$ and $A_{x,f}$ follow from a journey plan associated with each vessel (Segovia et al. (2022a)) and are generated at random (with $A_{x,e} \geq A_{x,f}$) in this paper. $W_x(k)$ is expressed as

$$W_x(k) = t - A_x, \tag{5}$$

where A_x is the actual arrival time of each vessel x at the drawbridge, and $t = kT$ the time. After this time the vessel is assumed to have arrived at the drawbridge and waiting in the berth area. Once a vessel passes through the drawbridge, the arrival time A_x is cleared and $W_x(k)$ is reinitialized to 0 according to:

$$W_x(k), A_x = \begin{cases} 0 & \text{if } t \geq A_x \ \& \ r_b = 0 \\ 0 & \text{if } A_x = 0 \ \& \ r_b \geq 0 \\ W_x(k), A_x & \text{otherwise} \end{cases} \tag{6}$$

If vessels are still waiting by the end of the simulation, all remaining vessels are assumed to pass at the end of the simulation.

3. AUTOMATIC DRAWBRIDGE SCHEDULER

The chosen approach of mainstream metering for simulating a drawbridge opening directly affects the flow of the segment in which the drawbridge is located. However, traffic in all segments is affected, with congestion forming upstream whilst downstream congestion clears. To encompass the effect of the drawbridge opening on the freeway, the 'total time spent' (TTS) is calculated. This metric, which is used for quantitative evaluation in a large number of traffic-control studies (e.g. Frejo and Camacho (2012)) is calculated as follows (Frejo et al. (2016));

$$\text{TTS} = \sum_{\ell=1}^{N_p} \Big[T\big(\sum_{i \in I_{all}} \rho_i(k_c+\ell) L\lambda + w(k_c+\ell) + w_r(k_c+\ell) \big) \Big] \tag{7}$$

The TTS is calculated over a prediction horizon N_p for all segments $i \in I_{all}$, L is the length of the highway segment, λ the number of lanes, and w and w_r the queues at the mainstream and on-ramp, respectively. The TTS is calculated every k_c control time steps, occurring every M model time steps k. Therefore, $k_c = \frac{k}{M}$.

The TTS calculates the sum of densities in all segments and takes in consideration the queues at the mainstream and on-ramps. Figure 2 displays the TTS differences in the traffic simulation with a single drawbridge opening at different times (k_b) compared to the simulation without a drawbridge opening. TTS almost always increases with a drawbridge opening and it is therefore almost never advantageous for vehicle traffic to open the drawbridge. An exception is the short peak in traffic at the beginning of the simulation where the drawbridge opening allows congestion to clear downstream by restricting inflow, decreasing TTS after reopening.

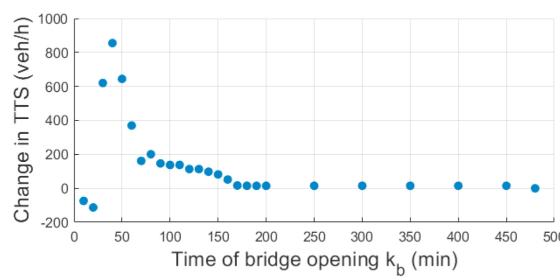


Fig. 2. Change in TTS as the drawbridge opens over time

A scheduler needs to be able to calculate a solution for any drawbridge, including busy waterways where most vessels require a drawbridge opening. In this study, the drawbridge, rather than opening for all vessels individually, which would result in a near-constantly opened drawbridge, vessels will berth in a waiting area and pass the drawbridge in batches upon opening. A scheduler should therefore be designed to schedule drawbridge openings for multiple vessels at the same time, as well as single vessels.

In almost all situations, the number of vessels in a waterway will be far less than the number of vehicles crossing the drawbridge. Furthermore, the macroscopic nature of the highway simulation and the microscopic nature of the waterway information means that individual behavior of vessels is easier to control than that of vehicles. It is therefore considered more appropriate to study the effect of the scheduler on highway traffic, whilst enforcing different types of behavior for waterway traffic. For this reason the default position of the drawbridge is also considered to be closed, meaning highway traffic can cross and waterway traffic cannot. Assuming a single unidirectional flow for both the waterway and highway along the drawbridge furthermore enables the study of the effect of the schedulers on highway traffic, as well as decreasing computational effort.

3.1 'Open-on-arrival' Scheduler

An elementary method of establishing a scheduler adhering to all considerations outlined above, is to simply open the drawbridge whenever a vessel arrives regardless of the level of highway traffic. Taking into consideration only the optimal arrival time $A_{x,e}$ of vessel x, a logic-based scheduler is thus created that is optimal for waterway traffic and does not take into account highway traffic. The 'scheduler' is created as follows:

$$r_b(k_c) = \begin{cases} 0 & \text{if } \frac{1}{T}A_{x,e} \leq k \leq \frac{1}{T}A_{x,e} + \tau_b \\ 1 & otherwise \end{cases} \quad (8)$$

This scheduler is the most advantageous to vessel traffic and is therefore useful as a control case when compared to schedulers that do consider highway traffic.

3.2 MPC Scheduling

The further two proposed scheduling approaches make use of Model Predictive Control (MPC). MPC is a control strategy that is based on a prediction model. The optimization of the MPC problem occurs through the minimization of a performance index $J(x(k^*), u(k_c^*))$. The performance index measures the performance of the system for a prediction horizon H_p according to a control sequence which can be reduced to a control horizon H_c to reduce complexity. This is known as the rolling horizon procedure. A method of solving the MPC problem is sequential quadratic programming optimization method (SQP), which is used in this study (Hegyi et al. (2005)). The control objective of this MPC controller consists of the minimization of the performance index:

$$\min_{[u(k_c|k_c), u(k_c+1|k_c) \ldots u(k_c+H_c-1|k_c)]} J(x(k^*), u(k_c^*)), \quad (9)$$

where k^* is the current known time step. The current known control time step k_c^* is therefore $k_c^* = [k^*/M]$. This is subject to the constraints:

$$\begin{matrix} \phi(x(k^*), u(k_c^*)) \\ \psi(x(k^*), u(k_c^*)) \end{matrix}, \quad (10)$$

where ϕ is the vector of nonlinear equality constraints and ψ the vector of nonlinear inequality constraints. The system equation is given by:

$$x(k+1) = f(x(k), u(k_c), d(k)), \quad (11)$$

with $Mk_c \leq k \leq (k_c+1)M$, and where x is a state vector that represents the system states, d a non-controllable input or disturbance vector, and u the input vector. In this paper, equation 11 is calculated using the METANET equations presented in section 2. Furthermore, the known initial state $x(k^*)$ and known disturbance $d(k^*)$ are given.

3.3 Waiting Time-Based Scheduler

The waiting time-based scheduler considers both highway and waterway traffic through the consideration of vessel waiting times after arriving at the drawbridge. $x(k_c)$ consists of traffic densities, flows, mean speeds, the queues at the mainstream and on-ramp, and the vessel waiting time.

$$x(k_c) = [\rho_i(k_c) \ \ q_i(k_c) \ \ v_i(k_c) \ \ w(k_c) \ \ w_r(k_c) \ \ W_x(k_c)]^T$$

$u(k_c)$ consists solely of the (continuous) main-stream metering rate $r_b(k_c)$.

$$u(k_c) = [r_b(k_c)]$$

To avoid the necessity for mixed programming, r_b is **not** considered to be binary. The scheduler can therefore find any continuous solution for $0 \leq r_b \leq 1$. Solutions for $0 < r_b < 1$ are ignored and implemented as 1 to avoid sudden alterations in traffic flow. The drawbridge scheduler can therefore not reduce flow partially. A drawbridge is considered open, vessels can only pass, and $W_x(k)$ can therefore only be reduced, when $r_b = 0$. Once r_b is set to 0, $r_b = 0$ for $k_b \leq k < k_b + \tau_b$, as described in equation 3.

$d(k_c)$ consists of the demand profiles of both the mainstream and the ramp, the number of vessels on the waterway and the optimal vessel arrival times.

$$d(k_c) = [d_o(k_c) \ \ d_{ramp}(k_c) \ \ N_x \ \ A_{x,e}]^T$$

The objective function $J_W(k_c)$ consists of the total time spent for highway traffic and the total waiting time of the vessels. As the waiting time already increases with k and is summed again over the prediction horizon N_p, J_W depends on the square of vessel waiting time.

$$J_W(k_c) = \sum_{\ell=1}^{H_p} \Big[((\text{TTS}) + T \sum_{x \in X_{all}} W_x(k_c+\ell)\xi_W \Big] \quad (12)$$

The scheduler thus has the ability to delay a vessel until highway traffic levels are lower or arriving vessels accumulate their waiting times. The choice between delaying waterway or highway traffic is regulated by the waiting time weight term ξ_W. If ξ_W is sufficiently large, the scheduler will avoid any waiting times at all.

3.4 Vessel Arrival Time-Based Scheduler

The vessel arrival time-based scheduler is created by using the two possible arrival times of the vessel, $A_{x,e}$ and $A_{x,f}$ as bounds for the drawbridge opening time. A drawbridge opening is scheduled at any moment between these two times, considering the predicted effect on traffic. The state space model used is identical to those in the previous example, with the addition of $A_{x,f}$ to $d(k_c)$.

$$d(k_c) = [d_o(k_c) \ \ d_{ramp}(k_c) \ \ N_x(k_c) \ \ A_{x,e} \ \ A_{x,f}]^T$$

The objective function $J_A(k_c)$ consists of J_W defined in equation 12 and a penalization term for the number of vessels remaining in the waterway:

$$J_A(k_c) = J_W(k_c) + \sum_{\ell=1}^{H_p} \Big[\xi_x N_{x,rem}(k_c) \Big]. \quad (13)$$

Here, $N_{x,rem}$ is the number of remaining vessels in the waterway that will have to pass the bridge during the simulation and ξ_x is the vessel weight term: a tuning factor. The following explicit constraint must be satisfied in all cases.

$$A_{x,f} \leq k_b \leq A_{x,e}$$

ξ_W is kept sufficiently high to ensure no vessel has a waiting time. The penalization term for the number of vessels remaining in the waterway ($N_{v,rem}$) is reduced when the drawbridge is opened, hence encouraging the scheduler to open the drawbridge. The constraint ensures this occurs between $A_{x,f}$ and $A_{x,e}$. Vessel traffic never experiences a delay with this scheduler, whilst some optimization with regard to highway traffic is permitted.

4. SIMULATION EXAMPLE

The schedulers have been simulated using MATLAB and the METANET parameters as found in Hegyi et al. (2005). The modelled road consists of a single link of 6 segments of length $L = 1$ km each. For simplicity nodes are not utilized and a single inflow and outflow from the link are assumed. An uncontrolled on-ramp is located at the fifth segment, the drawbridge is assumed to be situated at the third segment. A visual representation of the modelled highway stretch can be seen in Figure 3. Simulation parameters

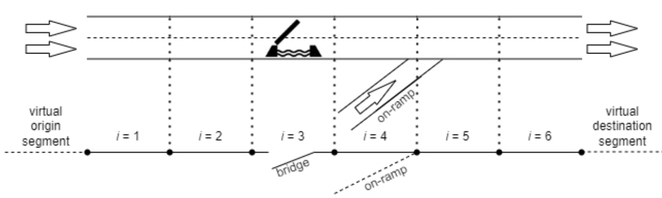


Fig. 3. The modelled highway link

are summarized in Table 1. The mainstream demand d_o is situated at a consistently high level of 3500 vehicles per hour until dropping to 1000 vehicles per hour after 2 hours. The on-ramp demand d_{ramp} peaks at 1500 vehicles per hour between the start and the first half hour and then drops to a constant 500 vehicles per hour.

Table 1. METANET parameters used in the simulation

C	ν_H	ν_L	τ	κ	δ	a
2000 $\frac{\text{veh}}{\text{h}}$	20 $\frac{\text{km}^2}{\text{h}}$	80 $\frac{\text{km}^2}{\text{h}}$	18s	40	0.0122	1.867
ρ_{crit}	ρ_{max}	v_{free}	T	L	λ	
33.5 $\frac{\text{veh}}{\text{km lane}}$	180 $\frac{\text{veh}}{\text{km lane}}$	102 $\frac{\text{km}}{\text{hr}}$	10s	1 km	2	

The average TTS and waiting times shown in Table 2 for all three schedulers validate the intended design of the schedulers. The open on arrival scheduler is most advantageous to the vessels, as it disregards the TTS. The waiting time scheduler benefits highway traffic as TTS decides the passing time of the vessel and vessels experience delays. The arrival time scheduler, which places bounds on k_b but does consider TTS, falls in between.

Table 2. Performance of the schedulers for 10 randomly generated sets of A_x, $n_x = 6$

	Open on Arrival	**Waiting Time**	**Arrival Time**
TTS (veh.hrs)	4613.56	4167.09	4424.44
$\sum W_x$ **(min)**	0	148.5	0

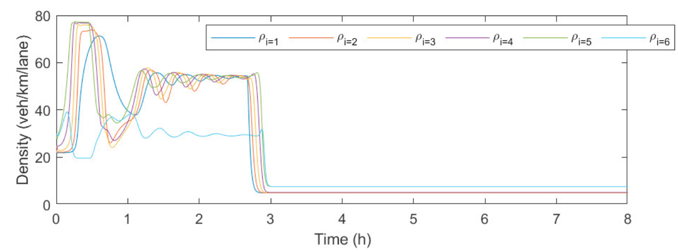
The waiting time-based scheduler is deemed most applicable for a highway drawbridge implementation due to the greater reduction in TTS. Its results are therefore discussed to highlight scheduler functioning without discussing the results for the other schedulers further. Results for this scheduler are shown in Table 3 for the demonstrated set of A_x. $\xi_W = 1 \times 10^{-7}$ is chosen.

The scheduler is tuned to allow vessels to pass the drawbridge only after vessels have waited for some time. The specific length of waiting time at similar levels of traffic

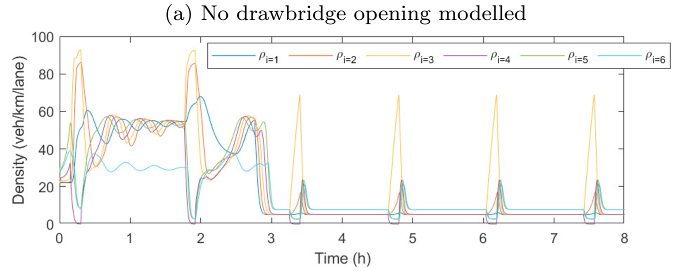
Table 3. Vessel arrival, vessel waiting and bridge opening times and length of bridge opening for the waiting time based scheduler

$A_{x,e}$ (hours|min)	k_b (min)	t_b (min)	W_x (min)
0.28|17	9	9	0
1.67|100	106	9	6
3.06|183	195	9	12
4.44|267	279	9	12
5.83|350	362	9	12
7.22|433	445	9	12

flow is arbitrary and controlled by the size of ξ_W, permitting a political or economic choice regarding the delay experienced by vessels or vehicles. The scheduler demonstrates consideration of highway traffic with the increase in vessel waiting times when traffic levels are lower, and the relative disruption to traffic of a drawbridge opening therefore larger. This can be seen in Figure 4a. The waiting time is doubled by schedulers after the first two arrivals, coinciding with the high demand for the first 2.5 hours and low traffic demand for the last 5.5 hours.



(a) No drawbridge opening modelled



(b) 6 drawbridge openings scheduled and modelled

Fig. 4. Highway traffic densities per segment with no-control and the waiting time-based scheduler applied

The response of traffic to the drawbridge opening can be seen in Figure 4b. Although densities are increased due to the peak in demand in the beginning of the simulation, a relatively high, fluctuating level is maintained for the first 2.5 hours, after which constant low densities occur of about 5 veh/km/lane before the onramp. Traffic recovers and stabilizes quickly after drawbridge openings. It is furthermore notable that the first drawbridge opening occurs before the arrival of the first vessel, corresponding to the large congestion at the beginning of the simulation. Therefore, the drawbridge opening is acting as the mainstream metering on which the drawbridge modelling method was based to regulate highway traffic.

The prioritization of vehicular or vessel traffic through tuning ξ_W is visualized in Figure 5. As weights increase, waiting times reduce sharply. Due to the limited number of vessels, reductions in waiting time occur stepwise when ξ_W is reduced as waiting time values need to be compounded

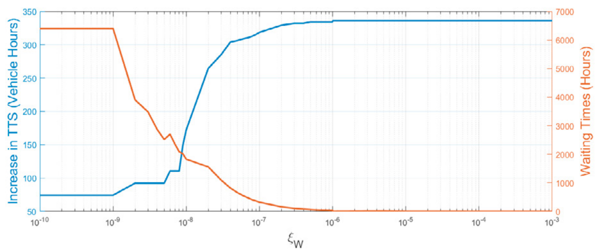


Fig. 5. The relation between increasing weights and the increase in TTS (in blue) and waiting times (in orange)

by the arrival of a further vessel to trigger an opening. Vessel arrival times are not synced to the control time step, thus vessel waiting times may not reach zero entirely even with very large values of ξ_W.

5. CONCLUSIONS AND FUTURE WORK

A highway drawbridge operation was simulated using the METANET model based on the model presented in Hegyi et al. (2005). Modelling of a drawbridge opening was achieved through adaptation of the traffic control measure 'mainstream metering.' This proved to be a suitable method that could represent the physical repercussions of a drawbridge opening with minor alterations to the model. Waterway traffic was chosen to be modelled by generating information necessary for the schedulers without a macroscopic model for the flow of vessel traffic.

Three schedulers were proposed and tested on the basis of the effects of a drawbridge opening on both types of traffic. An 'open on arrival' scheduler was used as a base case, where the drawbridge opens immediately when a vessel arrives. The 'waiting time-based' scheduler considers vessel traffic using a sequential quadratic programming method of model predictive scheduling through the consideration of vessel waiting times after arriving at the drawbridge, making a trade-off between vessel and vehicle delays. The 'arrival time-based' scheduler similarly relies on a time window of possible vessel arrival times, choosing a drawbridge opening time optimal for highway traffic within that window. The novel schedulers have been shown to make verifiable choices regarding the scheduling of drawbridge openings as the drawbridge opening times demonstrate a constant response with different traffic levels. The trade-off that is implemented between vessel waiting times and total vehicle time spent (TTS) through increasing weight terms demonstrates tuning schedulers can be achieved by modifying cost function parameters.

Further case studies and real-life implementation of the drawbridge scheduler would yield important data that can be used to further tune decisions and validate the functioning of both model and scheduler. Including further vessel information, varying bridge opening times τ_b with traffic levels, and placing constraints on the schedulers to bound the number of waiting vessels and vehicles would allow the model to be applied to such an implementation. Furthermore, the indirect assumption of discrete signalling by only rewarding the objective function when $r_b = 0$ can be improved by transforming r_b to a discrete variable. Discrete optimization of traffic control variables is possible and already done for both discrete variable speed limits and reversible lanes (Frejo et al. (2016)).

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