AN AGENT-BASED MODEL OF NAVIGABLE INLAND WATERWAY TOW OPERATION PROCEDURES

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ABSTRACT

Transportation modeling in the context of climate change-induced extreme weather events is critical to understanding and improving the resilience of our transport systems as we move further into the 21st century. Among transportation modes, navigable inland waterways in particular face severe challenges to their future reliability due to the impacts of extreme weather events. While the economic implications of inland waterway operational efficiencies on commercial shipping have been studied in detail for several decades, the effects of tow operation procedures enacted during adverse river conditions resulting from extreme weather events are less well understood. In this paper, we describe a model of a waterway segment that simulates stakeholder decision-making and tow operator behaviors with the goal of providing stakeholders with insights on the possible benefits of Waterway Action Plans (WAPs) as operational guidance documents. Simulations run for a test area of the navigable inland waterway system indicate that operational procedures recommended in WAPs may have a significant impact on waterway operational efficiencies, further suggesting that the model may be a useful decision-support tool for waterway stakeholders.

Keywords: agent-based model, inland navigation, waterway action plan, operation procedures

BACKGROUND

One of the primary missions of the U.S. Army Corps of Engineers (USACE) is to maintain navigable inland waterway channels and navigation locks (*1*). These activities help support a major segment of the U.S. national economy, primarily by facilitating shipment of raw materials and other bulk goods. The economic value of inland waterway commerce in the U.S. was estimated to be approximately $214 billion in 2012 (*2*). Over the last decade, extreme weather events have caused billions of dollars in direct and indirect damages to the waterway system. These disruptions can lead to long delays in barge shipping traffic, which in turn lead to additional costs being passed on to consumers and the public at large as shipping costs correspondingly rise (*3*). Climate science suggests that the frequency and severity of extreme weather events is likely to increase; therefore the ability of waterway stakeholders to prepare for and respond to adverse river conditions resulting from extreme weather events will be crucial to maintaining resilient supply chains (*4, 5, 6*).

Optimization of tow travel on inland waterway navigation systems is a well-studied area with many examples of models that simulate lock improvements, lock congestion, lock queuing procedures, barge-tow configurations, waterway reliability, and tow speed adjustments using various statistical and discrete event simulation techniques (*7, 8, 9, 10, 11, 12, 13*). However, many of these models rely heavily on historical data and/or theoretical probability distributions, making their application to extreme river conditions, for which little high-resolution recorded data is available, problematic (*12, 14*). Moreover, many of the available navigable inland waterway models are focused on consumer demand-induced commercial shipping traffic as a driver of waterway efficiency and do not explicitly consider waterway conditions or procedural changes in waterway operations that may impact points other than navigation locks in their analyses and simulations (*10, 11, 12*).

MODEL FRAMEWORK

By aggregating data, or reducing interactions to a set of key events, statistical and probability driven discrete-event simulation models reduce system complexity and computational requirements. These models are typically fairly simple for waterway stakeholders to utilize and explain, and validation of these models of navigable inland waterway systems generally indicate that they effectively represent aggregate properties of the system under consideration (*8, 10, 12, 14*). However, due to the infrequent nature of extreme weather events, the complexities of adverse river condition tow travel and their impacts on waterway operational efficiencies cannot be accurately characterized using techniques that rely on historical data, aggregation, and/or spatial or temporal snapshots. While data of sufficient resolution and record length is not readily available to analyze the historical impacts of adverse river conditions, information in the form of procedural guidance documents is available. These guidance documents may be used as a framework for modeling the decisions and behaviors of waterway stakeholders during adverse river condition events in order to illuminate some of the impacts of adverse river conditions on the inland waterways.

Waterway Action Plans

Recognizing that changing behavioral patterns during events that lead to adverse river conditions can be difficult, and that delays in adapting to extreme situations typically lead to undesirable results, in 2007 the towing industry, USACE, and U.S. Coast Guard (CG) developed sets of operational guidelines for the navigable inland waterways (*15*). These Waterways Action Plans (WAPs) include recommended actions (for various river stage, dam opening, or flow trigger points) for waterway operators (tow operators, lock masters, and CG officers) to guide their decision-making when adverse river conditions such as high stage, high flow, ice jams, and low water are encountered. Given a presumed increase in frequency and severity of extreme weather events such as heavy precipitation events and droughts that may result in high stage, high flow, or low water river conditions, the WAPs are expected to be utilized with greater frequency in the future. However, to date little is known about the effectiveness of the WAPs in maintaining optimal waterway efficiency.

In this study, we approach the problem of inland navigable waterway transport under adverse river conditions using a behavioral tow movement model and procedural controls based on the WAPs. In this first version of the model, we use a simplified scheme for representing shipping activity and river conditions in order to demonstrate proof-of-concept and clearly elucidate the possible implications of WAP guidelines for barge delivery rates, tow speeds, locking and lock queueing times, and origin-destination transit times. This approach allows us to simulate basic commercial activity on a generalized segment of the waterway system subject to WAP recommended operating procedures and generate testable hypotheses about the extent to which operational procedures recommended in the WAPs influence the efficiency of waterway operations.

Agent-based Modeling

The idea of emergence, that some system level patterns can arise from the bottom-up due to the interactions of many autonomous system components, can be useful for identifying critical behaviors, decisions, and interactions that have the potential to significantly impact entire systems of individuals and groups (such as the navigable waterways) and serves as the foundation for agent-based modeling methodology (*16*). We assume that observed system-level trends in operational metrics for the navigable inland waterways can be explained in part by emergence as the waterways are a system that is composed of many autonomous and interacting agents or stakeholders (*13*). As historical data on stakeholder (tow operator, lock master, and CG officer) actions and corresponding outcomes under adverse river conditions are both sparse and lacking in detail, it is difficult to deduce what the implications of increased adverse river conditions may mean for the waterway network, or what impact WAPs may have on operational metrics by analyzing aggregate system properties. However, by using a decision-making approach and simplifying the system to a set of stakeholder decision controls and corresponding behavioral processes, the problem of data shortage is avoided and the impact of the WAPs becomes of predominate importance. This enables underlying impacts of operational procedures that may not be seen in analysis of historical data due to aggregation of information with other factors, such as rapid hydrological changes, increased/decreased shipping demand, or changes in convoy configuration, to be recognized. The impacts of behavioral changes implied by stakeholder decisions regarding operational procedures are particularly important in the context of extreme weather event induced adverse river conditions which challenge waterway operators to break out of habitual decision-making patterns and adapt to unusual conditions.

The aforementioned waterway segment model was constructed using NetLogo, a free and widely-used multi-agent modeling platform (*17, 18*). Since agents are modeled as singular entities that follow specified behavioral patterns of action and interaction, this approach reduces model complexity by eliminating the need to have a complete understanding of all the system level interactions and instead allows the degree of complexity to be programmed into agents' behavioral models (*19, 16*). While in some cases this approach may lead to over-simplification of a system, it does allow one to study the relative importance of certain types of behaviors or decisions by simply tuning parameters in agents' behavioral models (*16*).

The basic waterway segment model takes into account agent interactions with the environment, with other agents of the same type and between agents of different types, while representing the system at time intervals capable of capturing an agent's ability to anticipate and react to situations (Figure 1). The model also visualizes, in a simplified form, tow movements on the waterway segment and different steady-state river conditions, in order to facilitate participatory interactions with waterway stakeholders (*13*).

MODEL DEVELOPMENT

In order to model the possible impacts of operational procedures on tow movements, guidelines provided in the WAPs were reduced to a set of modifiable parameters that relate either directly or indirectly to specific recommendations made in the WAPs. Table 1 provides examples of how specific recommendations from the WAPs relate to user controlled parameters and procedures in the model (*20, 21, 22*). While all of the parameters that can be controlled in the model influence tow movements, decisions regarding parameter settings and the control of these parameters fall under the purview of different waterway stakeholder groups (i.e., tow operators, lock masters, and CG officers). The final set of parameters used in this model were validated by expert knowledge and were arrived at after demonstrating the model and soliciting feedback from tow operators, marine service company executives, and project managers at the USACE Nashville District office.

As the applicable range, combination of parameters, and/or specific value of the parameters used in the model vary significantly by waterway segment and by physical river conditions, the user interface for the model includes 15 unique controls that can be used to adjust the parameterized Waterway Action Plan procedures. This configuration allows the model to be generally applied to different waterway segments and encourages local participation by allowing stakeholders to provide parameter values applicable to specific waterway segments, waterway disruption scenarios, and river conditions via direct interaction with the model. In the case that stakeholders do not participate directly in setting parameter values for simulations, or where stakeholder experiential knowledge of adverse river conditions is limited, a range of parameter values and parameter combinations should be tested to provide a suite of outcomes possible given minimally informed settings.

Model Environment

The developed waterway segment model is designed to accommodate any generalized river segment of up to 300 miles in length with bi-directional traffic and constant river conditions. Within these bounds, some of the complexity of the physical environment can be tailored to meet the user's needs. Bridges and navigation locks may be added at any river mile on the main-stem of the segment using a multi-selection list. Each navigation lock is assumed to have only one operational lock chamber. In addition, a single one-way traffic zone may be established with user designated start and end points which are represented as orange buoys in the center of the channel. The model is graphically represented by a three-dimensional environment of cubic patches where, along the x direction, one patch represents one mile of waterway segment length. Waterway segments are visualized as completely straight along the x-axis with a constant width and a stepwise elevation increase/decrease at dams in the z-direction. The y and z directions of the model as well as the size of the graphical representations of the tows, barges, locks, buoys, and bridges are not to scale, but are sized to aid visual representation of the system. System updates occur at regular intervals called ticks, which represent a time period of 30 minutes. This time interval represents the largest common time period capable of representing variability in locking times. The tick counter is linked to a date-time clock that allows users to monitor the time of day, which is also visualized in the model as a backdrop of either light blue for daytime or black for nighttime.

This model uses a simplified shipping scheme with a single origin-destination pair for each heading (upstream and downstream) located at the start and end of the waterway segment. Tow traffic and barge shipping demand originating at both upstream and downstream ends of the segment are randomly generated at regular intervals during daytime hours. Immediately after spawning near docks located at the segment ends, tows load as many barges as possible given user imposed constraints on the *horsepower/barge-ratio* and *maximum-tow-size* parameter settings. Tows then proceed the full length of the segment, and shipment receipt is assumed upon a barge arrival at the opposite end of the segment. No fleeting area stops, deliveries or pickups, tow reconfiguration activities, or directional changes are available mid-segment in this version of the model.

Model Mechanics

Due to the slow pace of waterway tow movements (in comparison to other transportation modes), and the use of the Automatic Identification System (AIS) which provides tow pilots with real-time information on the speed and location of all AIS-enabled tows, vehicular traffic models based on acceleration and deceleration rates of preceding vehicles were deemed to be inappropriate (*23, 24*). Instead, the combination of anticipatory and reactionary tow behaviors implemented in the model are governed by "safe-distance" based traffic rules, where individual tow movements (updated each tick) follow behavioral rules that are designed to prioritize maintenance of the user-specified safe distance between themselves and preceding tows (*25, 26*). Conservative tow movement procedures are used to ensure that collisions do not occur between tows, an event which rarely occurs on the waterways, and which is not typically the result of poor decision-making by a tow operator, but rather random physical processes, such as the sudden onset of a strong cross-current (*21, 22*). At each tick, tows evaluate their speed and distance in relation to their heading; user specified safety-based minimum and maximum speeds;

other nearby tows, bridges, one-way zones, and locks; and with consideration of environmental factors such as time of day (Figure 1). The developed tow behavioral model includes a default behavior routine, situation-specific sub-routines, and thresholds which, if crossed during the above mentioned evaluations, trigger changes in tow behavior by enabling situation-specific behavior routines. This results in a complete tow behavioral model that allows tows to adapt to several different situations that might be encountered on a waterway segment.

The parameter *min-trailing-distance* defines the minimum allowed distance that should be retained between tows and provides a trigger for alternating between anticipatory and reactionary tow behaviors. While not directly referenced in the WAPs, this parameter can be considered as one possible way of "exercising caution", a frequent recommendation encountered in WAPs. If a tow gets within the *min-trailing-distance* of another tow, reactionary movement rules take over and the tow automatically reduces its speed (such that it cannot traverse the existing distance between itself and the tow ahead within the next two ticks), or comes to a full stop, even if the speed of the preceding tow is faster. However, if a tow is not within the *min-trailing-distance* of the preceding tow, it will check to see if it anticipates traversing the existing distance between the two tows within the next two ticks (i.e., If you continue moving at your current speed and the tow in front of you stops, will you run into it in the next hour?). If the answer to this query is affirmative, the tow reduces its speed such that it will continue traveling as quickly as possible provided that if the preceding tow were to stop, it should remain at least the *min-trailing-distance* behind. When passing is enabled by the user (*Allow-Passing* On), anticipatory passing logic is implemented such that a tow will not attempt to pass a slower tow unless it anticipates that it can safely move ahead of the tow. This evaluation compares the relative travel speeds of the two tows as well as any oncoming tows, and ensures that the position in front of the preceding tow will not be occupied.

Similar anticipatory logic is used to handle movement past bridge obstructions and through navigation locks and one-way zones. With each tick, tows search ahead a distance equivalent to the farthest they could possibly travel (given a set *maximum-speed* parameter) in 30 minutes (one tick interval). If a bridge, lock, or one-way zone is found to be within that distance, a set of additional evaluations and corresponding responses are carried out. For bridge evaluations, the time-of-day and the possibility that multiple bridges may need to be passed are checked. Multiple bridges within five miles of each other are evaluated by tows as a single bridge passage segment with only the starting and ending bridges visible. For upcoming locks, the time-of-day and a tow's position within the lock queue are evaluated. When a one-way zone is directly ahead, a tow's position within the one-way queue and the presence of tows currently navigating the one-way zone are considered. Queuing for both navigation locks and one-way zones is based on a first-in-first-out (FIFO) procedure. When locking tows request locking restriction information from the lock manager which is used to calculate locking time as the size of the tow, divided by the *Barges-per-lockage*, multiplied by the *Lockage-time*. In all cases, tows continue to obey rules of tow-to-tow positioning and speed adjustment while also adjusting their speed relative to the position and character of the obstruction and to the settings of nighttime movement parameters.

DEMONSTRATING PROOF-OF-CONCEPT

To evaluate the model and generate testable hypotheses regarding the impacts of WAP-based procedures implemented in response to adverse river conditions on waterway operational efficiency, we use a simplified representation of a navigable section of the Cumberland River. The Cumberland River is a major tributary of the Ohio River located in the southern United States with over 300 miles of navigable waterway and 4 navigation locks which are operated by the USACE (*27*). The Cumberland River basin, which includes the Cumberland River and several tributaries, is also home to nine hydropower plants as well as several flood control projects (*28, 27*). While this system is quite complex, the basic model tested simplifies the navigable waterway segment to a set of origin-destination points located in Barkley Lake and Old Hickory Lake, with assumed constant river conditions. The locations of locks (Cheatham Lock & Dam and Old Hickory Lock & Dam) and bridges were taken from navigation charts of the Cumberland River and the list of tows operating on the river and their horsepower are from U.S. Army Corps of Engineers Lock Performance Monitoring System (LPMS) data for the Cumberland River for the year 2013 (*29*). Speed ranges for upstreaming and downstreaming tows used in the simulation are based on calculated lock-to-lock travel times for the Cumberland River from 2013 LPMS data after outlier removal.

In order to ensure that the model performs in a reasonable manner, and to improve understanding of the possible implications of WAP implementation, we ran 42 simulations of different waterway navigation scenarios, collecting outputs for more than 17,000 time points for each scenario. The simulations test the individual and combined effects of possible WAP actions (Table 1) that might be implemented under various extreme river conditions by varying the setting of individual parameters and testing parameter permutations to obtain a distribution of outcome metrics. Outcome metrics for this study include average travel speeds, the number of barges delivered per tow travel time, hours spent locking or in lock queues daily, and transit times.

Simulated Traffic Patterns

The output of simulations run for the test area using the developed inland waterway navigation model indicate that tow movement behavioral rules and parameterized WAP operation procedures generally perform as expected. Examination of the average tow speed by river mile of the model environment, as seen in Figure 2 (a and b), shows that average speeds tend to decrease as tows move away from their origin point or away from a lock they have just navigated, with this trend being more pronounced when no passing is allowed (Figure 2b). This indicates that on average tows tend to reduce speeds as they approach tows ahead of them, and that when passing is not allowed on the waterway this occurs with greater frequency. These figures also clearly show that tows reduce their speed as they approach navigation locks (river miles 116 and 183) and come to a complete stop while locking. Evaluation of average tow speeds by river mile when the operational parameter *Stop-at-Bridges* is enabled indicates that tows slow and come to a stop when approaching bridges during the night, as average tows speeds approach zero at river miles where bridges are located. In addition, examination of average tow speeds by river mile after implementation of a one-way-zone shows that tow speeds decrease and approach zero as tows approach the start of a one-way zone.

Plots of average tow speed by time of day illustrate the effect of operational procedures that restrict nighttime travel. Scenarios for which no nighttime travel restrictions are implemented show little variation in average tow speeds by time of day (see example in Figure 2c) while scenarios which do have nighttime travel restrictions show large variations in average tow speed with time of day. Implementation of the *Stop-at-Bridges* procedure, as seen in Figure 2d, leads to a gradual decrease in speeds over the course of the night as more tows reach bridges and come to a complete stop before rapidly increasing to their desired travel speed early in the morning. A similar, but more pronounced trend is observed when additional nighttime travel restrictions, such as prohibiting night locking (*Night-Locking* Off), are added to the *Stop-at-Bridges* procedure.

Impacts on Operational Efficiency Metrics

Summary statistics were calculated for each simulation and trends for key operation metrics were examined where sufficient information was available. The changes in simulated speed profiles that result from implementation of different operational procedures logically translate into increases and decreases in the key operational metric of tow transit times. Transit time is simply the amount of time it takes for a tow to travel from the starting point to the ending point of the modeled segment. When controlling for all parameters except for target, maximum and minimum speeds, there is a clear and significant trend (p-value< 0.000) of increasing transit time with decreasing target speeds indicating that this aspect of the model meets logical expectations. Where sufficient information was available, various parameters were examined as moderating factors of this trend. When the *Allow-Passing* procedure is examined as a factor in this trend relating target speeds and transit times while controlling for nighttime travel restrictions (Figure 3a), it is apparent that target speeds have a greater impact on transit times when passing is not allowed. The *Stop-at-Bridges* parameter also impacts the trend of transit time with target speeds (Figure 3b). When controlling for the passing procedures, the more restrictive conditions (*Stop-at-Bridges* On) lead to a greater effect of target speeds on transit times. While not surprising, these plots do suggest that as operational procedures become more restricted, target speeds have a more pronounced impact on transit times.

Another operational metric of interest in commercial shipping is barge delivery rate (number of barges delivered per transit time). This metric is dependent on both the transit time and operational procedure parameters relating to tow size (the number of barges carried by each tow). As expected, Figure 4 shows that increasing barge carrying restrictions by decreasing the maximum allowed tow size (*Maximum-Tow-Size*) or increasing the required tow horsepower for each barge (*HP/Barge-Ratio*) significantly decreases barge delivery rates when all other parameters are held constant at normal operating condition settings. Comparison of the plots presented in Figure 4 suggests that tow horsepower-to-barge ratio requirements are more restrictive than maximum tow size requirements and can lead to greater decreases in the ability of shippers to deliver barges.

The amount of navigation time spent locking or waiting in lock queues are also key operational metrics for waterway navigation systems. The amount of time each tow spends locking each day is related to locking restrictions and tow size restrictions. The effect of lockage restrictions on average daily locking times, as presented in Figure 5a, suggests that when

Maximum-Tow-Size and *HP/Barge-Ratio* are held constant at normal operating conditions, reducing the number of barges allowed per lockage increases the average daily locking time. (The upper limit for the barges allowed per single lockage restriction is based on the physical size of the lock, and in severe weather conditions the barge allowance may be reduced for safety reasons.) These increases in average daily locking times can be attributed to a greater frequency of double lockages which occur when two single lockages are needed to pass the tow and all its barges through the lock. When the amount of time needed to complete a single lockage (this parameter is dependent on river conditions) is examined as a factor in this trend, simulation results imply that *Lockage-Time* has a greater impact on average daily locking times than *Barge-per-Lockage* restrictions.

Trends for average daily lock queuing times are less clear than those for average daily locking times, as lock queueing times are related to locking times themselves as well as traffic conditions resulting from implementation of passing, one-way-zones, and nighttime travel restrictions. Significant trends for average daily lock queuing times were not detected without controlling for other parameters and insufficient information was available when all controls are enabled to accurately detect trends. However, Figure 5b indicates that while increases in *Lockage-time* may slightly increase time spent in lock-queues, restricting locking at night produces large increases in lock queue times.

CONCLUSION

The long term resilience of our navigable inland waterway system is clearly dependent on how well we are able to manage the waterway during expected increasingly frequent adverse river conditions. However, little is currently known about how waterway operational procedures implemented during adverse river condition events impact efficiencies of inland waterway operations. By utilizing an agent-based modeling approach, and framing decision-making behaviors of individual stakeholders around adverse river condition response procedures recommended in WAPs, hypotheses about the impacts of waterway operator procedural decisions on navigable inland waterway segment efficiencies can be generated.

The developed waterway segment model simulates tow travel on a time-step basis, and the observed logical variations in travel speeds due to traffic rules, time of day, and locations of navigation locks and other obstructions to navigation, indicate that the model performs in a reasonable manner. Our analysis of simulated data from WAP guideline implementation under steady-state conditions for a simplified representation of the Cumberland River navigable waterway suggests that reducing target speeds and implementation of nighttime travel restrictions, such as stopping at bridges and mooring at night, may have the greatest impact on average tow transit times and overall system capacity for the test area. The predicted strong effect of target speeds on transit times implies that river flow conditions, particularly for upstream travel speeds, may impact average transit times during adverse river conditions induced by heavy precipitation events. Simulations generated by the model suggest that in such cases where flow conditions force tows to adopt slower travel speeds, additional travel restrictions may increase the strength of the negative effect of tow speeds on transit times. Parameters that influence tow size appear to not have a large impact on transit times, but may impact barge delivery rates.

The model described herein provides a simplification of the navigable inland waterway system that serves as a platform for conducting an initial evaluation of the impacts of the WAP procedures that guide waterway stakeholder actions during adverse river conditions resulting from extreme weather events. While the model passes a basic proof-of- concept test, it has yet to be experimentally validated using observed data, limiting its current use to hypothesis generation. All conclusions drawn from use of the model should be verified using alternative means. Traffic logic validation using AIS real-time tow movement data is currently in progress and may support future use of the model as a stand-alone planning tool for optimizing waterway stakeholder decisions that influence tow operation procedures. In addition, modifications of the model to include incorporation of an approximated linear hydrodynamic model and basic hydrology related travel constraints, as well as the inclusion of tow fleeting areas where barges may be loaded/unloaded and where tows may change their direction of travel are underway. This more advanced functionality will provide additional realism to the inland waterway navigation model while maintaining a simplified structure that will allow users to test the impacts of waterway operator procedures implemented in response to adverse river conditions. Model code and supplementary data are available upon request.

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TABLE 1 Selected Recommendations from WAPs and Corresponding Model Actions.

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FIGURE 5 Average simulated locking times (*a*) and lock queuing times (*b*). Trend lines are displayed as thick dashed lines and thin dashed lines indicate 95% confidence bands.

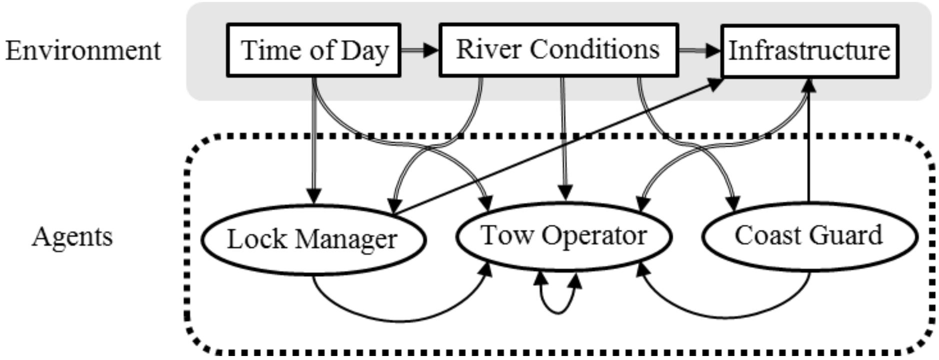


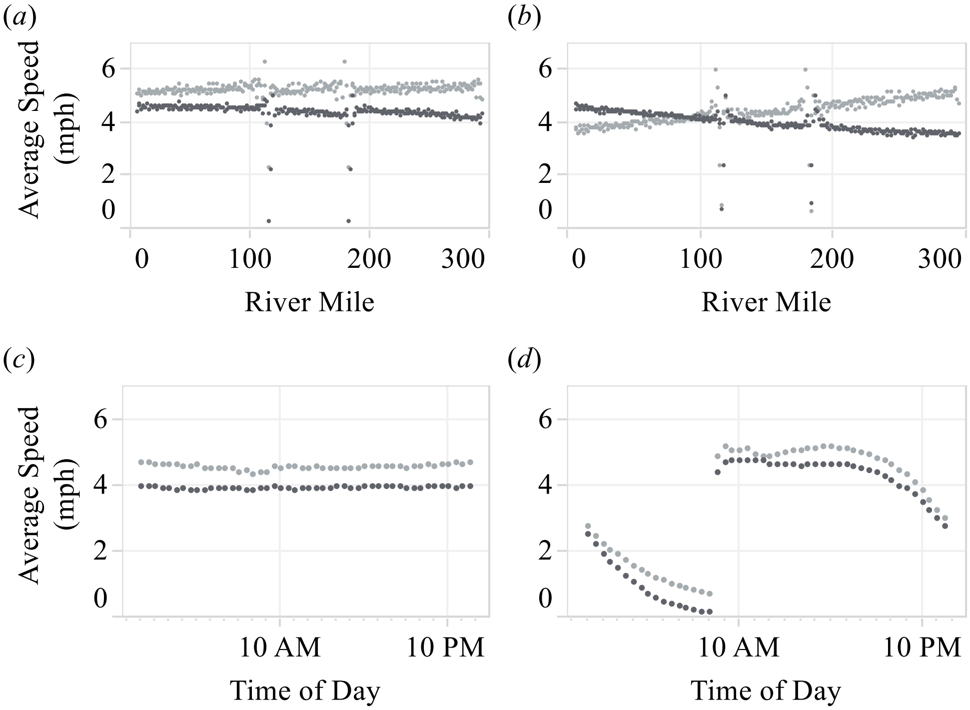
FIGURE 1 Primary interactions that can be modeled in the basic version of the waterway segment model.

TABLE 1 Selected Recommendations from WAPs and Corresponding Model Actions.

Agent	**Waterway Conditions in WAPs**[a]	**Procedures Recommended in WAPs**	**Possible Actions**[b]
Tow Operator			
Responsible for moving barge freight on the waterway; make navigation decisions regarding physical movements of the tows.	High Water, High Flow (*21*)	Safety Advisory in effect. Advise the use of caution and minimize wake. (*21*)	Reduce *minimum-speed*, *maximum-speed*, *upstream-target-speed*, and *downstream-target-speed*; Increase *min-trailing-distance*; Turn *Allow-Passing* Off
	Extreme High Water, Extreme High Flow (*22*)	Mariners are advised to exercise extreme caution when transiting under bridges due to hazardous conditions. (*22*)	Turn *Stop-at-Bridges* On; Reduce *minimum-speed*, *maximum-speed*, *upstream-target-speed*, and *downstream-target-speed*; Increase *min-trailing-distance*; Turn *Allow-Passing* Off
	High Water, High Flow, Low Water (*21*, *22*)	Mariners are advised to consider horsepower capability and tow size. (*21*, *22*)	Increase *Horsepower/Barge-Ratio* and/or Reduce *Maximum-Tow-Size*
	Extreme High Water (*21*)	Caution in passing/meeting situations. (*21*)	Turn *Allow-Passing* Off; Increase *min-trailing-distance*
	Extreme High Water, Extreme Low Water (*21, 22*)	Consider vessel restrictions including minimum 250 horsepower per loaded barge, tow size limits or daylight operations only. (*21, 22*)	Increase *Horsepower/Barge-Ratio* and/or Reduce *Maximum-Tow-Size*; Turn *Mooring-at-Night* On
Lock Manager			
Responsible for operating the lock for passage of tows from one waterway segment to the next; make decisions on lockage availability and requirements.	High Water, High Flow (*20*)	Tow configuration will be limited to no greater in length and width than would be 9 jumbo barges made up in a 3x3 configuration. (*20*)	Reduce *Barges-per-Lockage*; Increase *Lockage-time*
	Extreme High Water, Extreme High Flow (*20*)	Tow may not be separated for multiple lockage. (*20*)	Reduce *Maximum-Tow-Size*; Increase *Lockage-time*
	High Water, High Flow (*22*)	Mariners are advised to exercise extreme caution when navigating locks due to hazardous conditions. (*22*)	Reduce *Barges-per-Lockage*; Increase *Lockage-time*; Turn *Night-Locking* Off
Coast Guard			
Responsible for overseeing safe navigation on the waterways; officers set and maintain safety zones	Extreme High Water, Extreme High Flow, Extreme Low Water (*21, 22*)	Implement Safety Zone. (*21*, *22*)	Turn *Activate-One-Way-Zone* On and set location of *One-way-buoys*
	Extreme High Water, Extreme High Flow, Extreme Low Water (*22*)	Recommend one way traffic. (*22*)	Turn *Activate-One-Way-Zone* On and set location of *One-way-buoys*

[a] *Multiple possible conditions resulting in a WAP recommendation separated by a comma.*

[b] *Alternative actions separated by a semicolon.*



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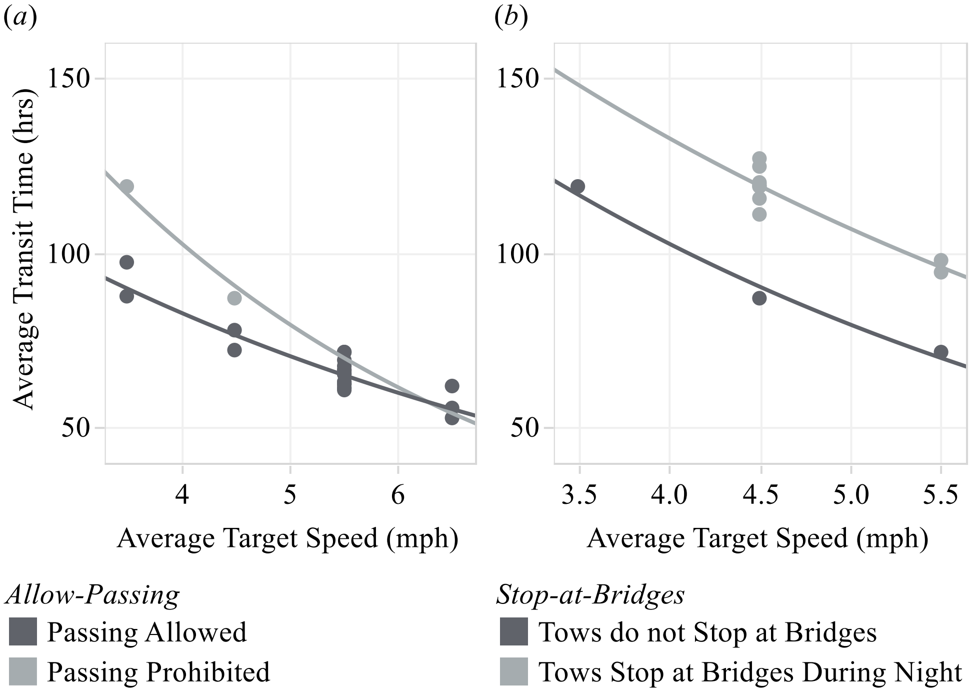

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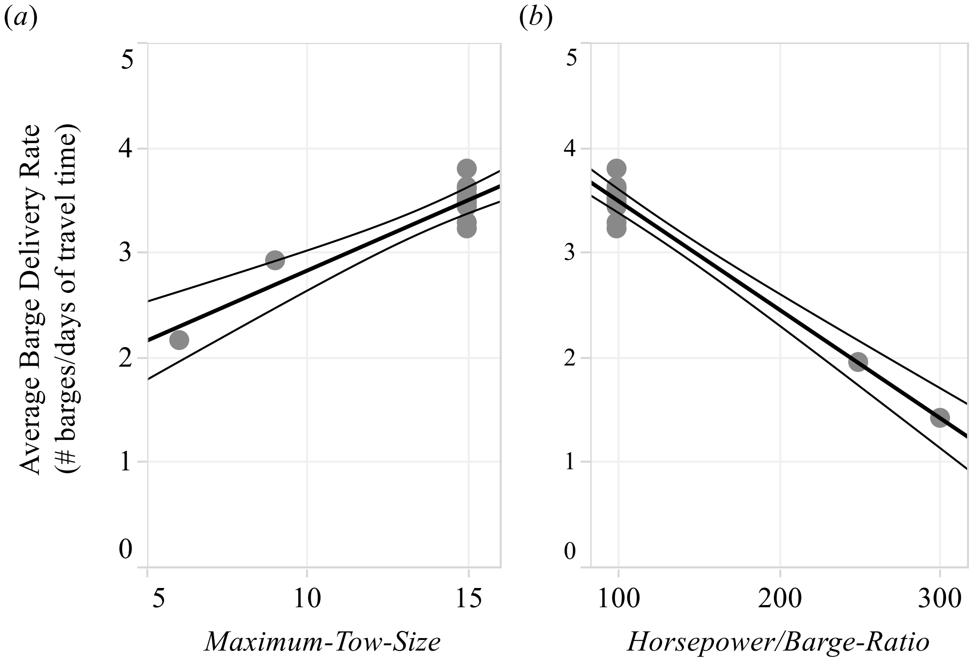

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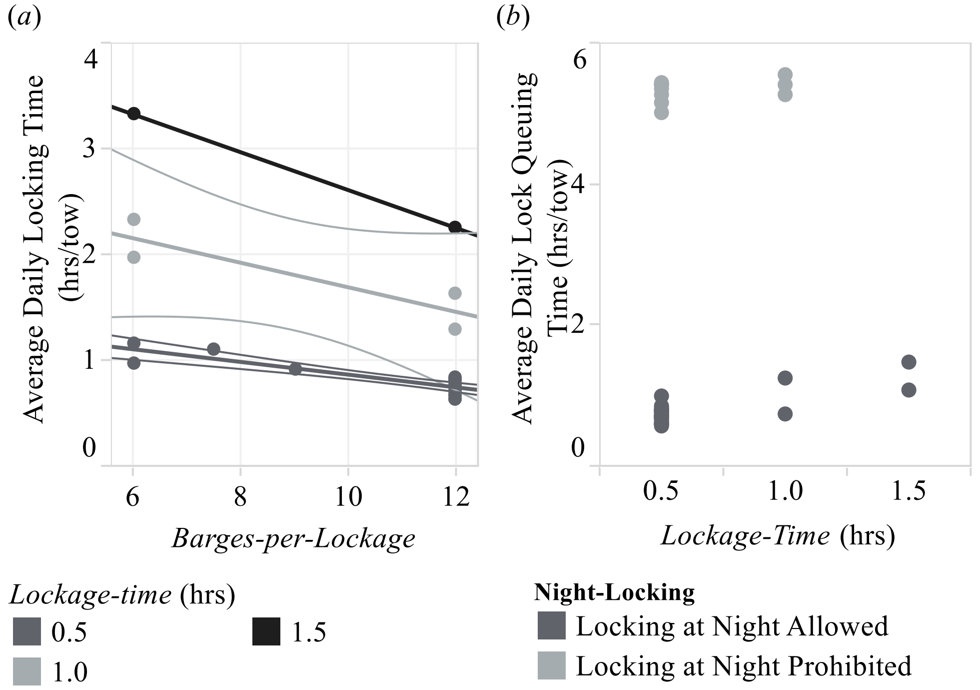

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