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Hierarchal Object-Oriented Models for Management of Narrow Passageways

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Abstract

Narrow passageways are a significant source of traffic congestion and delay in transportation networks. With traffic volumes expected to increase significantly in the foreseeable future, the effective management of these passageways is needed to mitigate the undesirable impact of these bottlenecks on transportation system safety, performance and cost. In an effort to address the significant challenges associated with the analysis, design, and implementation of appropriate management operations for narrow passageways, an object-based model for the management of narrow passageways in the transportation network is developed. The object model is developed in two steps. The first step identifies high-level management functionality, objects, and associated data/information sources that are common to all narrow passageway applications. In the second step, functionality of the object model is customized to the specific needs of the narrow passageway application domain (e.g., waterways and work zones).

Keywords: waterways, object-oriented model, transportation
Jel Classification: C600, C610, R490

Introduction

In transportation networks, narrow passageways occur where the width of a transportation link is insufficient to permit operation of two-way traffic at normal speeds of operation. Example of narrow passageways occuring in transportation networks are: waterway, work zone, tunnel, one-lane bridge, and railroad applica-

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tions. They have be imposed either by natural physical restrictions as is the case of waterways or under investement in capacity due to the high costs that would be incurred as in the case extreme terrain condiotions. As a result, congestion, accidents, and delays are common problems. The effective management of these systems is needed to mitigate the undesirable impact of bottlenecks on system safety, reliability, performance and cost. In a broader sense a port entrance or a runway of an airport can be also considered as narrow passageways as they tend to be the narrow points in traffic "funnel". While the management of traffic on a one-lane bridge might be handled with a sign indicating who has the right of way, the implementation of appropriate management operations for large scale transportation systems can be very complex and expensive, in part, because modern communication systems must be integrated with automated scheduling, surveillance and tracking systems.

In an effort to address the significant challenges associated with the analysis, design, and implementation of appropriate management operations for narrow passageways, this paper attempts to develop an object-based model for the management of narrow passageway problems in transportation systems. The object model is developed in two steps. First, we identify high-level management functionality, objects, and associated data/information sources that are common to all narrow passageway applications. In the second step, functionality of the object model is customized (or extended) to the specific needs of the narrow passageway application domain (e.g., waterways and work zones). By creating a hierarchical object model for narrow passageway management operations, we hope that in the near-term, engineers will be provided with improved methods for analyzing the system behavior of complex management operations, designing and upgrading new systems through improved procedures for requirements generation, and reusing established system architectures and systems integration across application domains (e.g., decision making procedures for management operations guided by information sources obtained from Geographic Information Systems (GIS)).

Scope of Narrow Passageway Problems

Fig. 1 shows the scope of narrow passageway management operations that will be addressed in this paper. The upper-most level represents management operations that are common to all narrow passageway problems. At the second level, management operations for specific narrow passageway problems is obtained through extension and specialization of the high-level generic management operations.

The object hierarchy shown in Fig. 1 is derived from a wide range of real world transportation systems. For railroad, work zone and narrow waterway applications, sophisticated techniques of system analysis and control are justified by the life-critical safety risks and adverse economics of poor system throughput. As a case in point, university researchers have worked with the Federal Highway Administration to study optimal geometry and appropriate management system control policies for traffic flow in highway and urban street work zones (Schonfeld, 1999). Even more sophisticated management operations are justified when high volume traffic streams need to transit narrow passageways embedded within large-scale transportation networks. For example, research (Dai, 1998) has been conducted to understand and design traffic control policies for inland waterways containing locks (e.g., the Mississippi River, Danube River). Preventing accidents and environmental disasters, reducing congestion and lengthy traffic delays, enforcing laws, and collecting tolls are all essential tasks of a traffic management system.

Countries such as Panama and Turkey have already made large investments in the development of enhanced traffic management systems for narrow waterways. A notable application is the Bosporus Straits, a sinuous 19-mile long straight with 12 abrupt turns and treacherous currents, that is a passageway for nearly 50,000 tankers and cargo vessels a year. There is also very heavy ferry traffic which connects the European and Asiatic sides of istanbul and which crosses the straits The number of crossing by intra-city ferries and other shuttle boats is approximately 2000 daily carrying approximately 1.5 million passengers. It has become an artery for the world's oil because of the oil exports from the former Soviet republics. Traffic jams and shipwrecks have become quite common. In December of 1999, a Russian tanker split in half and polluted the water and coastline with 900 tons of fuel oil. In April of 1999, a 9,000-ton cargo ship ran out of control and crashed into the shoreline of Bebek, an Istanbul neighborhood on the Bosporus Straits. Alarmed by the growing safety, environmental and economic threats of the Bosporus's overcrowding, Turkey hired Lockheed Martin to build a $20 million system that will improve the control of ship traffic through the use of radar and satellite technologies (Moore, 2000). Another notable application is the Gaillard Cut, which is an eight-mile narrow segment of the Panama Canal that can only support unidirectional traffic at any one time. The delays in transit service caused by this part of the canal lead to significant increases in fuel cost, service costs, and depreciation costs for vessels and their cargo. Delays may become even more significant as traffic demands continue to grow (Panama, 1998). Moreover, due to the strategic nature of the Panama Canal as a transportation and trade link between the Pacific and Atlantic Oceans, and the strong need for expeditious transit service, the Panama Canal Agency is creating an enhanced traffic management system and wide the Gaillard Cut as part of a one-billion dollar canal improvement program (Panama, 1998). Another case of a narrow waterway is the Corinth Canal in Greece. The canal is 6 km long and connects the Ionian and Aegean sea trough the Corinth and Saronian gulf. At water surface the canal is just 24 meters wide. A preliminary vessel management system has been installed to facilitate traffic across the canal.

The traffic control management system that we are proposing includes a traffic management information system (TMIS) and effective communications between the control center and traffic streams within the narrow channel. The TMIS has at its disposal a variety of technologies for collection and transmission of data (e.g., cameras, sensors, GPS, radio communications). Control centers employ the TMIS to collect and process information sources, such as details on the position of traffic, weather, and safety information.

Object-Oriented Model

With the need for a generic approach to modeling, design and management of narrow passageway problems in place, we now present: (1) details of the object-oriented model formulation for a two-tiered traffic management system, and (2) extensions of the formulation to waterway and work zone applications. We employ the Unified Modeling Language (UML), a collection of seven diagram types capable of modeling transportation system behavior and structure. Key aspects of front-end development include a use-case model for a visual representation of high-level management functionality and a domain model for understanding the management system.

Development Process

As shown on the left-hand side of Fig. 2, the development process for object-based modeling begins with the construction of a use case model, containing use case diagrams representing high-level system functionality. In this initial phase of life cycle development, high-level requirements are gathered through goals and scenario analysis (Austin, 1999). Second, a domain model consisting of a conceptual static structure diagram and collaboration or sequence diagram is constructed. These diagrams portray the real world domain. In this analysis phase, conceptual class diagrams are useful for representing the system structure. Collaboration and sequence diagrams show the flows of communication among objects needed to support required system behavior. System design alternatives are created by mapping models of system behavior onto the system structure. Finally, state-chart and deployment diagrams are useful representations for detailed system-level design, subsystem design, and implementation – these latter stages of development are beyond the scope of this paper, however.

Use-Case Model

A use case is simply a set of system scenarios tied together by a common user goal (i.e., aspect of system functionality). A use case specification contains:

- A list of actors (actors are anything that interfaces with the system externally);
- A boundary separating the system from its external environment;
- A description of information flows between the actors and individual use cases;
- A description of normal flow of events for the use case, and
- A description of alternative and/or exceptional flows.

Use case diagrams are a convenient way of showing the way in which a real-world actor will interact with the system, the use cases with which they are involved, and the boundary of the application. A collection of use cases is known as a use case model (Ambler, 1998). The development of a use case model provides order to the elicitation and representation of high-level system functionality, which in turn, leads to the generation of requirements, identification of system objects and their interaction.

Fig. 3 is a use case diagram for a "general purpose" traffic management system. The names of the actors, which are drawn as stick figures, are control center, traffic controller, driver, and country/authorities. At the heart of the traffic management system is the control center. The control center monitors and tracks traffic in passageways to maintain safety, ensure security and law enforcement, protect the environment, while also scheduling and optimizing traffic operations. It monitors weather conditions and traffic congestion, and dispatches quick-response units to respond to emergencies. The major points of contact for a control center are:

1. The traffic controllers, who implement the traffic policies imposed by the control center. Controllers are physically located at the narrow passageway and can either be humans or automated devices. For example, lock operators and tugboats can be controllers at inland waterways and canals while traffic lights, automated switches and other electronic devices can be controllers at tunnels, one-way bridges and railroads.
2. The authorities, who enforce the rules of passageway operation and respond to an emergency (for this problem domain, a country is a political establishment that establishes rules and regulations, and in some cases tolls).
3. The drivers, who transit the narrow passageways. Drivers receive route and departure time information from the control center aimed at avoiding congested passageways. So-called "top-of-the-line" Traffic Management Information Systems would also allow drivers to send positioning information and traffic updates to the control center.

The use case diagram does not indicate the objects and flow of data/information in the transportation system.

Domain Model

With the use case model in hand, the purpose of the domain model is to build an understanding of the problem domain relevant to the system development. This is an analysis phase that describes the system structure and the flow of information and interactions among objects in the system. Fig. 4 shows the objects that make up the system structure -- rectangles represent the various classes and the roles they take within the application, and the lines between the classes represent the relationships or associations between them together with their multiplicity. UML notation allows for the representation of a variety of multiplicity relationships. For example, every route has at least one passageway and every passageway can belong to one or more routes. In this case there is a one-to-many relationship in both directions.

The class diagram in Fig. 4 can be customized (or extended) to class diagrams for any narrow passageway application domain. For example, the transportation mode class can be extended to be either a vehicle, train or vessel class depending on the narrow passageway application. Likewise, the narrow passageway class can be extended to be a one-lane bridge, railroad, waterway, work zone or tunnel class. The new extended class inherits all the attributes and methods of the class that was extended. For example, a tunnel class inherits the ID, location, capacity, length, width and the rest of the attributes of the narrow passageway class. It will also inherit all the methods and behavior of the narrow passageway class. More generally all the classes in the class diagram of Fig. 4 can be extended to classes that are appropriate for the specific narrow-passageway problem domain.

In the object-oriented approach to system development, each specific thing is an object (e.g., Lincoln Tunnel, English Channel Tunnel, Baltimore Tunnel, etc.) and the type of thing is called a class (in this case Tunnel). Objects are defined by the data/information they contain, methods for manipulating the data/information, and additional properties that cover and encapsulate (or protect) the object for undesirable communication/updates from other objects (Austin, 1999). The result is a collection of interacting objects – an object can send another object a message, or an actor can send an object a message (Austin, 1999; Satzinger, 2000). In the UML notion, the flow of information between objects, which defines the system behavior, is shown using sequence and collaboration diagrams.

Extension of the Object Model to Narrow Waterways

The economic benefit of the object model formulation occurs through reuse of modeling constructs when high-level formulations are extended and customized to specific narrow passageway domains, such as waterways. As a first step in this modeling process, the waterways application domain requirements are generated by expanding the use cases in Fig. 3 to the custom made use cases shown in Fig. 5. The actors who interact with the specialized system and the high-level functionality are the same in both use case diagrams. However, as expected, management of narrow waterways requires more specialized functionality as in the case of transit entry and fulfillment subsystems. While these subsystems may require more complex operations and information systems than similar systems in other transportation networks, the use case model in the object-based formulation can be applied to the management of narrow waterways.

The structure of the waterway problem domain is also derived from the high-level conceptual class diagram for narrow passageways. Fig. 6 shows the conceptual class diagram for a management system in the waterway application. Classes such as the vessel and waterway are extensions of the transportation mode and passageway, respectively. The vessel class inherits all the attributes of the transportation mode while including additional information such as the attributes, tonnage and nationality. The specific element (vessel) is fully consistent with the general element (transportation mode in this case). Also, the coast guard and traffic controller objects are extensions of the authorities and traffic controller objects in Fig. 4. The objects that are new and specific to the waterway application are the lock and tugboat. A vessel could, but might not be, accompanied by one or more tugboats through the narrow channel. This is indicated by the zero-to-many relationship between the vessel and tugboat. Also, the route could have zero or many locks with one or more lock operators. Another relationship that is specific to the waterway application is that every vessel makes one transit request while in the general case in Fig. 4 it is not mandatory for a transportation mode to make a transit request as in the case of cars passing through a work zone. The fact that all vessels make transit requests to pass through the channel, makes the transit booking and scheduling ever so important for a traffic management information system (TMIS) in the waterway application.

TMIS Subsystems

The transit-entry subsystem has use cases for looking up transit availability, creating a new transit request, updating a transit booking and updating the transit schedule. This subsystem processes transit inquiries, requests and cancellations from drivers who call the control center. A transit request may be made as the vessel approaches the narrow channel or beforehand and there may or may not be a toll associated with the transit. Once a transit request is received and a booking is made, the transit schedule is automatically updated by an algorithm that will help reduce delays and congestion and the transit information is sent to the driver and traffic controller at the waterway.

Transit scheduling and traffic control policy can provide for more efficient transits through narrow waterways, especially when the narrow waterways are embedded within a large-scale waterway network. For example, a vessel may be redirected to an alternate route in order to avoid a congested waterway. Providing an alternate route based on a distance vector or link state routing algorithm (Huitema 1995) can help reduce transit times at congested waterways. Also control policies such as dispatching disciplines at waterway locks can also help provide better transit system performance. For example, Ting and Schonfeld used simulation to analyze different dispatching disciplines such as "first come first serve" (FCFS) and "shortest processing time first" (SPF) at a series of waterway locks in the Mississippi River. They concluded that SPF was more preferable to the FCFS dispatching discipline for reducing delays at each lock. Simulation is a powerful tool for determining the optimal transit route and control policy (Ting, 1998) and the object model approach is a powerful method for understanding the requirements, the structure and the behavior of a system.

The Geographic Information System (GIS) produces maps with the position of all the objects in the waterway channel (see Fig. 5). This integrated map is sent to traffic controllers and drivers who are in transit. The ability to locate all the objects in the channel provides for additional safety and more efficient operations. In addition, the GIS can be used to model the actual channel in different ways so that it is easier to manage. For example, a GIS can model rivers as a set of lines that form a network. A linear network model can then be applied to analyze ship traffic. A river could also be modeled as an aerial feature with an accurate representation of its banks, braids, and navigable channels on the river. Finally, a river could be modeled as a sinuous line forming a trough in a surface model. From the river's path through the surface, the information system can calculate its profile and rate of descent, the watershed it drains and its flooding potential for a prescribed rainfall (Evans, 1993). Using GIS to model the narrow waterway and locate the position of all ships on a map, can help the control center, traffic controllers and drivers make intelligent decisions and manage the most difficult areas of navigation.

Finally, the Channel Advisory Subsystem sends updates on channel conditions to operators, controllers, drivers and the coast guard. Congestion, inclement weather, accidents and violation of rules and regulations all require special attention. An information system can keep track of such conditions and alert all the actors of these special circumstances. Such an advisory system can help provide safe and efficient transits for all ships.

Extension of the Object Model to Work Zones

A second application for the management of narrow passageways is work zones in highways and urban streets. A work zone is the section of the roadway where there is construction work and maintenance operations taking place. Models of this problem domain are complicated by the temporary and changing nature of the construction work, and the need to avoid unnecessary traffic delays and accidents through the judicious scheduling of lane closures. Building upon the general use case diagram shown in Fig. 3, the work zone use cases are customized to include transit scheduling and scheduling of the work zone itself. This ephemeral narrow passageway disrupts normal traffic flow and it leads to serious safety risks for drivers, who transit through the work zone, and maintenance workers, who are exposed to traffic and vulnerable to any accidents or collisions in the work zone. The drivers must process a lot of information as they are guided through the work zone by human or electronic traffic controllers and maintenance workers must establish a safety buffer between themselves and the traffic so they may do their job without any major safety risks. Fig. 7 shows a use case diagram for the management of work zones. All the actors, with the exception of a maintenance worker, are the same as in the general model in Fig. 3, however, as expected there is more specialized functionality as in the case of work zone setup and fulfillment subsystems.

The domain model for the work zone problem domain contains the conceptual class diagram shown in Fig. 8. Once again some classes are extensions of the general class diagram in Fig. 6 while the rest of the classes are more specialized for the work zone application. More specifically, the work zone and vehicle classes inherit all the attributes and methods of the narrow passageway and transportation mode classes, respectively. In addition to all the attributes of the narrow passageway class, the work zone class contains information about the operating costs and occupancy period. The traffic controller class in Fig. 8 is extended to either a flagger or a control device (e.g., a barrel or electronic sign). This generalization is indicated by the upward arrow in the figure. Traffic controllers may either redirect traffic to alternate routes or provide right of way passage for alternating traffic in a one-lane work zone. Equipment, maintenance worker and work zone scheduling classes are also explicitly associated with the work zone application. The work zone scheduling class is the most important distinction for this narrow passageway problem domain.

TMIS Subsystems

The work zone TMIS consists of a setup subsystem, a fulfillment system, a work zone advisory subsystem, and GIS and transit subsystems. The setup subsystem has use cases for looking up feasible work zone setups and updating the work zone scheduling. It processes information about the traffic conditions of the roadway in which the work zone will be setup, and it returns feasible work zone options. The time of day for work zone scheduling, the traffic volume and capacity of the roadway, the roadway network surrounding the work zone, and the geometry of the roadway and different work zone options are all important factors in selecting the most appropriate and effective work zone and traffic control strategy (Federal Highway Administration, 1981).

As traffic volume and demand approaches or exceeds work zone capacity, queues begin to form and could be sustained for a considerable amount of time. Researchers (e.g., Dixon, 1998; Schonfield, 1999; Schrock, 2000) have employed a variety of analytical and simulation methods to estimate the queue length at different work zones in different locations (and hence estimate expected delays and cost), and used this information for decision making (e.g., scheduling traffic and work zone operations, lane closures, merging preferences, speed control and compliance, use of advanced-warning devices for traffic control, and to optimize work zone length). Once the work zone has been selected and put in place, the work zone fulfillment subsystem should store information regarding the status of the work zone and the completion of road maintenance and the work zone. Such a subsystem helps maintenance workers and managers keep track of progress and any outstanding issues.

The Geographic Information System can be used to view the topology surrounding the work zone and to estimate traffic volumes before and after the setup of a work zone. Estimating traffic volumes can then help planners determine the most appropriate dimensions (e.g. width and length) for a work zone. Also, GIS can be used to monitor traffic in adjacent roadways and evaluate the chain affects of a work zone on the roadway network as a whole. As in the waterway application, the work zone advisory subsystem records congestion, weather updates, accidents and violations in the work zone, allows the control center to inform drivers, traffic controllers, maintenance workers and police of adverse and possibly hazardous conditions in the narrow passageway.

Finally, as in other narrow passageway applications, the transit subsystem determines the optimal route for traffic traveling near or through the work zone. The optimum route and traffic control policy can be determined by analyzing the traffic conditions and by performing simulations. In the work zone application a transit request is made when a vehicle passes over a tube-counter. The transit requests are used to monitor congestion at the work zone. Also, the transit request is not associated with a transit booking and toll as in the waterway example. Work zone and transit setup and fullfillment subsystems as well as GIS and work zone advisory subsystems can be used to increase safety, minimize delays and reduce operating and user costs at these high-risk ephemeral narrow passageways.

The application of the model in work zones can be broadened to include the management of the transit system in the cisty as a whole as is the case of Athens, Greece, which preparing to host the 2004 Olympic games. A number of transportation projects are currently constructed or upgrated and as a result the city is witmessing massive delays due to work zone congestion problems. In a number of cases there is a single lane in each direction for vehicle traffic, route deviations and metro station closures. During the Olympic games due to priority schemes that would be implemented for the Olympic family, a reduction in the number of lanes allocated for general traffic is envisaged further necessitating the need for a traffic management application.

Conclusions and Futuer Work

The hierarchal object-oriented model views a system as a group of interacting objects that work together to accomplish system objectives and satisfy system requirements. Key benefits in the object approach to problem solving include:

1. Reuse of high-level system architectures across narrow passageway applications.
2. Ease of extension to specific application domains, like waterways, work zones, railroads, tunnels and one-way bridges.
3. Representation and solution of problems of a relatively high level of abstraction.

Together, these benefits improve problem solving productivity. For front-end development, use-case and domain models provide a visual representation of high-level system functionality and system design. Engineers can use this methodology for behavior analysis of complex operations, to design and upgrade new systems, and to reuse and integrate geographic information systems, transit scheduling, and channel advisory information systems. We anticipate that a TMIS integrated with state-of-the-art technologies like GPS, cameras, sensors and radio communications will lead to improvements in transit time, throughput, and reductions in cost associated with delays and accidents. These advances will be of great use to countries, organizations, and companies that are currently developing and investing in very complex and expensive traffic management systems.

Our medium-term research plans are to automate the development process by designing and building an interactive problem solving environment for the front-end development of surface transportation systems. Research tasks include finding ways to store UML diagrams in object-relational databases (see, for example, Small world, 2001) and connect front-end developments/graphics with high-level back-end systems analysis and rule-checking procedures. By providing preliminary feedback on system performance, we hope that the latter will define boundaries between the feasible and infeasible domains, and simplify problem formulations by representing (and possibly eliminating) technology options and management procedures early in the development lifecycle.

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Figure 1
Hierarchy of Management Problems

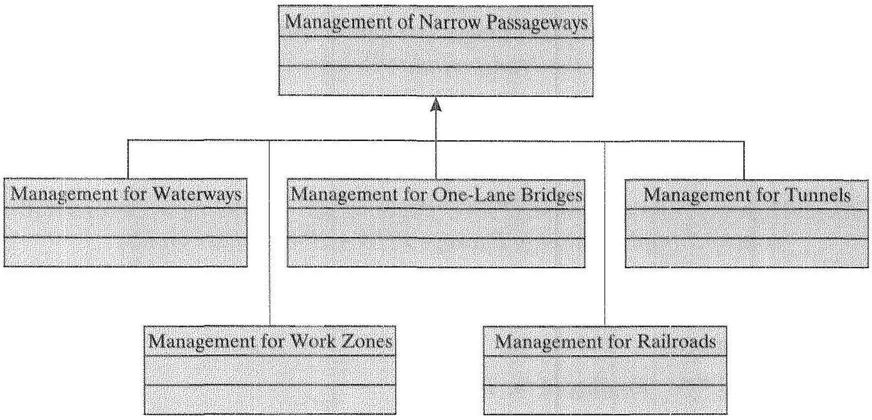

Figure 2
Development Process of Object-Based Model

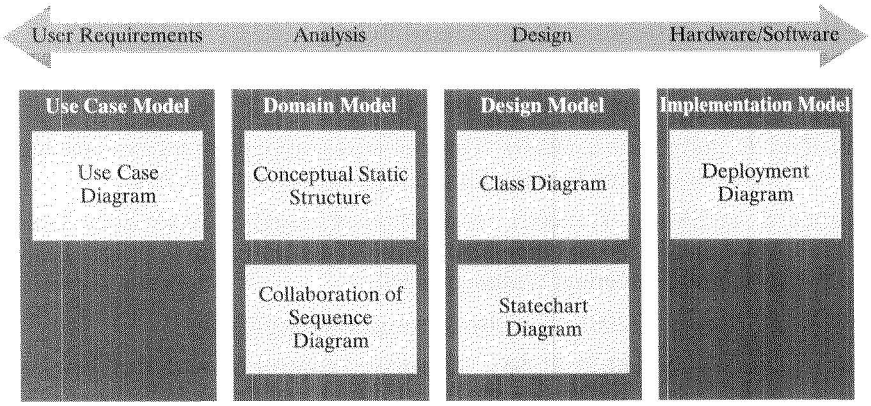

Figure 3

Use case diagram of a high-level Traffic Management System

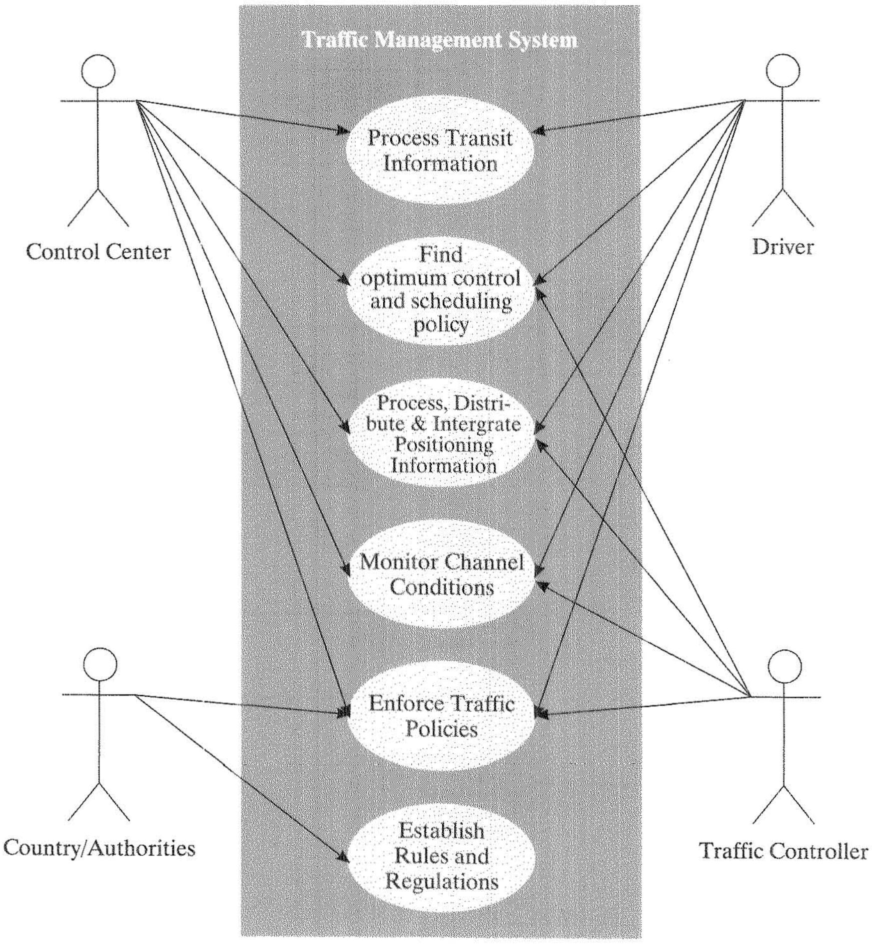

Figure 4

Conceptual Class Diagram for High-Level Traffic Management System