

A Real-time Integrated Transport/Communication/Database Architecture to Support Traffic Simulation

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ABSTRACT

This research aims for an establishment of a global center that will advance the knowledge in real-time human and goods transport. The focus of this paper is an approach for addressing the performance and feasibility issues with respect to a reliable and distributed traffic data communication network for optimal and secure routing of traffic. We present communications and database modeling for data acquisition via a high performance system. The proposed architecture is distributed, survivable, and reliable, thus capable of handling stationary and mobile sources of communication systems and integrating databases and dynamic traffic assignment into one comprehensive model. A case study on a visual interactive system for transport algorithms is discussed.

Categories and Subject Descriptors

C.2.1, C.2.4 [Computer Communication Networks]: Network Architecture and Design – *network communications, wireless communication*. Distributed Systems – *distributed applications, distributed databases*. H.2.4, H.2.7 [Database Management] Systems – *distributed databases*. I.6.2 [Simulation and Modeling] Simulation Support Systems Environments

General Terms

Algorithms, Management, Measurement, Performance, Design, Reliability, Experimentation, and Security.

Keywords

Dynamic traffic assignment, intelligent transportation systems, communications, distributed database, traffic simulation.

1. INTRODUCTION

Over the past 14 years the United States Federal Highway Administration (FHWA) has sponsored the development of the Dynamic Traffic Assignment (DTA) models that could be used for planning, given the inherent faults of the static traffic assignment,

and for Intelligent Transportation Systems (ITS) applications such as the estimation and prediction of traffic conditions. The DTA models will estimate time-varying network conditions by capturing traffic flow and route choice behavior. They are typically classified as analytical approaches, including mathematical programming, variational inequality and control theory approaches, or as simulation-based heuristic models.

Under this research effort, the FHWA developed two mesoscopic DTA models, the DYNASMART [1, 2] at the University of Texas at Austin, and the DYNAMIT [3] at the MIT. In parallel to this effort, Ziliaskopoulos at Northwestern University developed the RouteSim mesoscopic simulator and the Visual Interactive System for Transport Algorithms DTA (VISTA-DTA) [4]. Two additional DTA models developed in the US include TRANSIMS (Los Alamos National Lab., 2002, <http://transims.tsasa.lanl.gov>), and INTEGRATION [28].

A basic characteristic of these models is the utilization of a traffic simulator to emulate the traffic conditions especially for signalized systems where it is very difficult to capture the dynamics of traffic through analytical techniques. The subject of this paper is to introduce our development efforts and conceptual design of a comprehensive communications and database model for data acquisition via a distributed, survivable, reliable, high performance system that is capable of handling stationary and mobile sources of communication systems, and integrating a communications simulator, the new databases and dynamic traffic assignment into one data capture and analysis subsystem.

This research is to address the performance and feasibility issues with respect to a reliable and distributed traffic data communication network for optimal and secure routing of traffic. The communications and data traffic model is clearly a cyber-infrastructure challenge, consisting of distributed and reliable communications networking for collecting and processing traffic data, with a so-called reliable server pooling and distributed query processing. While these concepts suggest a focus on traffic, they will also be “expandable” for inclusion of other transportation impact data, such as noise, air quality and lethal chemicals. The communications and database modeling will be directed towards: (i) data acquisition via a distributed, survivable, reliable, high performance system that is capable of handling stationary and mobile sources of communication systems, and (ii) integrating a communications simulator, the new databases and dynamic traffic assignment into one comprehensive model.

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MobiQuitous 2008, July 21-25, 2008, Dublin, Ireland.
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The real-time traffic flow forecasting system we aim to develop is based on the VISTA (Visual Interactive System for Transportation Algorithms) DTA model. The VISTA software features a parallel data processing system that is compatible to the distributed data model presented in this paper. The model produces the DUE path for every vehicle from its origin to its destination. Under non-equilibrium conditions (e.g., incidents, short term traffic control changes) it produces the corresponding DTA path. Given each vehicle's path, aggregated traffic flow characteristics can be obtained at the network/sub-network level, path level, link/movement level, origin-destination pair, and vehicle class for any desired time period of the day. The DTA model will produce real-time traffic flow forecasts updated every few minutes based on the "Rolling Horizon" approach as envisioned by FHWA in the early 1990s when they started the development of DTA models. In parallel, the DTA model will be automatically calibrated using the data from the transport monitoring system.

The contributions of this paper are twofold: first, we summarize key observations on collecting traffic data and describe a high-level view of the communications and database modeling for data acquisition that takes advantage of ubiquitous computing; second, we show a comprehensive architecture with the proposed distributed data model, which will feed the VISTA software through the proposed communication system in a computationally efficient manner, so that VISTA will be able to complete its computations and produce the desired traffic flow measures of effectiveness and the vehicle paths and routes.

2. COLLECTING TRAFFIC DATA

A communication architecture based on server pooling [5-8] will be designed for secure and real-time transport operations. This paper introduces modified server pooling protocols and one type of distributed query processing algorithms tailored for transport networks. With the integration of server pooling and distributed database algorithms, the research will investigate critical communication issues including the communication bandwidth of the wireless communications, and the time to respond to an incident such as a non-compliant truck (e.g., a truck that has not been inspected at a clearance station is approaching a sensitive area). This section describes a high-level architecture suitable for collecting traffic data based on Uyar's results in extensive analysis of Internet Engineering Task Force (IETF) pooling protocols [6-13] and Kawaguchi's results in database and wireless application development [14-17].

2.1 Traffic and Roadway Surveillance

A canonical set of applications that must be supported by a robust and distributed communication system can be listed as:

- determining the status of a transportation system at every link and link movement of the network
- providing data to support dynamic optimal routing
- providing accurate maintenance data (e.g., using actual axle weights based on traffic flow as opposed to periodic maintenance)
- charging accurate tolls (e.g., based on the maximum axle load of each individual truck rather than charging the same toll for all trucks based on the number of axles)

- monitoring the status of a truck and/or a truck driver (e.g., special detectors can inform if a truck driver is sleeping, or having a heart attack, etc.)
- checking the legal compliance of a truck (e.g., if a truck should be at this location at this time based on its travel log kept by the sensors, or if it has the appropriate operating licenses, etc.)

For a transport system to perform the above applications in a secure and responsive manner, it requires the collection of the following data from stationary and mobile sources:

- *Vehicle Identification.* Vehicle identification can be provided through various technologies such as license plate, E-ZPASS tags – a toll collection system in the Northeast region- video image processing, etc.
- *Truck Image Identification.* Each time a truck visits a credential station a set of pictures will be taken and sent to a central computer through the communication system. In addition, each time a truck passes through a TRANSCOM's System for Managing Incidents and Traffic (TRANSMIT) Roadside Terminal (RST) reader – the TRANSMIT system is implemented in major roadways of the New York, New Jersey, Connecticut metropolitan region, weigh in motion (WIM) station, and toll plaza a picture of the truck would also be taken and compared to the images taken at the credential station. If the images and truck/driver credentials are the same, the truck will be allowed to continue its journey; otherwise the driver will be directed to either stop immediately or proceed to a designated exit of the roadway.
- *Location.* The location of the trucks will be known through GPS units, and/or E-ZPASS tags and/or cellular-based location technologies. The location of a truck can provide a real time monitoring system for security purposes, and provide real-time data on the impact of trucks on the transportation network.
- *Headway.* Over the past decade there has been considerable advancement in in-vehicle technologies and roadside detectors in the dynamic estimation of the headway between two consecutive vehicles.
- *Vehicle speed.* Truck vehicle speed is a contributing factor in truck accidents. Therefore, knowledge of the truck's speed will be necessary to provide cost estimates of the impact on accidents. Speed also affects the duration of the load applied to the pavement, with slower speeds increasing the damage to a pavement structure and shortening its life, particularly for those pavements of viscoelastic materials [18].
- *Axle load and tire pressure.* Knowledge of axle-load distribution and contact pressure, as well as speed, will be necessary for estimation of incremental damage caused by a truck [19]. The axle load is determined through weigh stations (WIM and/or static loading).

Different types of sources/sensors providing such truck traffic data, are considered: (1) stationary sources such as roadside beacon detectors, inductive loop detectors, microwave radar detectors, video image processing detectors, and weigh stations either WIM or static loading stations; (2) mobile sources such as trucks transmitting their location, headway, speed, driver health status, truck state and roadway compliance data.

Reliable Server Pooling (RSerPool) [6,7,8] is a framework for the reliable and survivable networking to provide highly available

services between clients and servers [20]. In RserPool servers are grouped into pools, each with an identifier and server selection policy. Three classes of entities are defined: Pool Users (clients), Pool Elements (servers), and Name Servers. If a client wants to access a server pool, any of the pool elements will be available.

The data collected from these stationary or mobile sources must be transmitted to one or more data processing centers. Depending on the application, some of the data will immediately be processed to generate results, whereas in other cases, the results may be sent back to another source (e.g., the toll amount for a truck must be transmitted back to the toll booth) requiring communication with multiple sources in the network (e.g., to the police in case of serious violations or emergencies, etc.).

The communication system must be capable of handling the large volume of the data with an acceptable high processing speed. In addition, the communication network must be able to handle stationary and mobile sources in a robust manner. The system architecture of the envisioned communication and database system should follow the guidelines provided by the United States (US) Intelligent Systems (ITS) architecture. These requirements suggest that a transportation system to support security and responsiveness requirements in truck operations must be distributed, survivable, and reliable with mobility support.

2.2 Reliable Server Pooling for Traffic Data Communication Network

In a traffic data communication system, each stationary and/or mobile sensor will be a Pool User (PU), which will constantly or intermittently exchange information with data processing centers. The processors and/or servers used in the centers will be the Pool Elements (PEs) of RSerPool. The PU to PE transmission may be unidirectional (e.g., a sensor sending truck location, speed, etc.), or bidirectional when the PUs need information from PEs (e.g., toll calculation results sent back to the sensors, or truck legality decision verdicts to let a truck pass through a bridge).

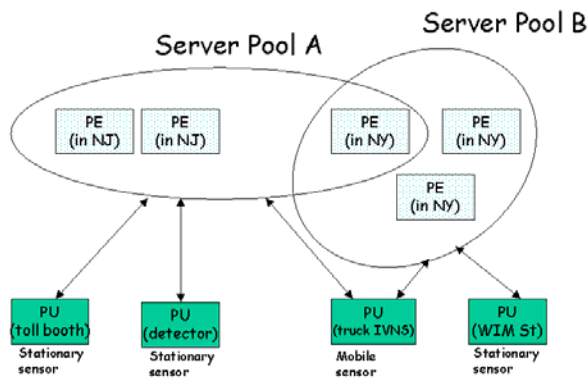


Figure 1 RSerPool with stationary and mobile pool users.

Formation of server pools is very flexible. In Figure 1, two server pools and several PUs representing both stationary and mobile sensors are depicted. Server Pools A and B may represent pools with different functionalities (e.g., Pool A can be for financial data and B for traffic management data.). The selection of PEs in Pool A spans different states, whereas in pool B the servers are local. Any PE can join in different pools simultaneously if the PE can

provide the services required by each pool (in Figure 1, one of the PEs located in NY is a member of both Pools A and B).

In Figure 1, suppose a toll booth (a stationary PU) is a member of Pool A. If one of the PEs of Pool A is congested (i.e., its response time is above an acceptable threshold), the PU will be switched to another PE in Pool A to provide load balancing within the pool. Similarly, in the case of a mobile PU, a truck, which is originally connected to a PE in NJ, can be switched to another PE in the same pool located in NY when approaching NY from NJ.

The home servers (not shown in Figure 1), each taking care of one or more PEs, PUs and pools, are collectively responsible to maintain the pools, such as registration of PEs in and out of pools, providing the list of available PEs in a pool to a PU who needs the service, etc. The communication media among the PEs of a pool and among the home servers can be LANs, WANs or MANs, depending on the distance and/or the performance requirements of the system. In the case of stationary PUs, the connection to PEs can be setup using dedicated lines, or phone lines depending on the system cost requirements and the availability of resources. Mobile PUs will use state-of-the-art wireless communication media that is commercially available. The concepts presented in this paper assume no dependency to a specific wireless technology. The current IETF RSerPool protocols, which are supposed to fully utilize the advantages of a new transport protocol, Stream Control Transmission Protocol (SCTP) [21,22], provide a starting point for addressing the reliability and survivability issues in a network.

Uyar et al. reported that the overhead introduced by the ASAP and ENRP protocols can be prohibitively large for mobile networks used in the mission-critical applications [9,10,11]. Uyar et al. suggested a set of enhancements these applications, including dropping the costly multicast messages among the servers, and introducing simple server advertisement mechanisms. Similar changes will be investigated for the IETF protocols to be deployed into the dynamic environment of a transport network.

2.3 Distributed Database Design

The following characteristics of a typical transportation system mandates the adoption of a distributed communication system rather than a centralized one: (i) the transportation system elements (such as sensors and data processing centers, etc.) operated and maintained by various agencies that are spatially distributed, (ii) different agencies own different parts of the traffic data, which needs to be integrated for optimal routing applications, (iii) mobile sensors (such as the sensors located in trucks) are required to communicate with different databases as their location changes (different jurisdictions, or different processing centers within the same jurisdiction), and (iv) the large volume data processed/transmitted for the applications of transport management prohibits a scalable centralized system.

The data elements collected from a set of PUs are stored in a database placed in a server pool in RSerPool. One or more PEs in a pool may be configured as dedicated database servers. There will be an independent database for each server pool; these databases are maintained in a distributed fashion as a whole. In this section, for simplicity, each pool contains a single server to focus on the distributed data among pools, rather than redundancy within each pool. But in reality, for reliability and survivability purposes, each server pool may have its redundant database servers. The

distributed database deployment permits to enforce local policies regarding the use of the data, i.e., a group of users that commonly share the data elements can have them placed at the server pool where they have local control. It is more economical to partition the application and do the processing locally at each pool. It is also easier to accommodate increasing amount of data for the possible expansion of processing and storage power in a pool.

An incoming sequence of traffic transaction records, each record having several attributes to be recorded, grows in an unbounded fashion. These records are stored in a database in a pool for some latest time window. We will treat the data collection of an active window as a data chronicle [23], which is similar to a relation, except that it is a collection of data sequences, rather than an unordered set of tuples in a relation.

A generic form of chronicle database consists of relations, chronicles, and persistent views. Relations are standard, as in any relational database. A chronicle can be represented by a clustered relation with an extra sequencing attribute. For the traffic data, values of the sequencing attribute are timestamps, each of which indicates the time the data is collected. Two types of update operations are made to the chronicle database: (i) insertion of data tuples, with the sequence number of the inserted tuples being greater than any existing sequence number in the chronicle (this is the only permissible operation under normal conditions), and (ii) merging of resent data tuples based on the appropriate event sequences, where the data is missing due to the malfunction of the measurement equipment at the road site or communication errors between PE and Pus (all re-sent data can be merged into the operational database based on the event sequence).

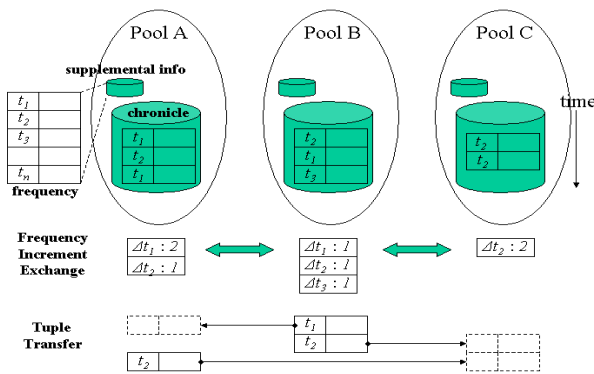


Figure 2 Distributed query processing for traffic analysis.

Treating a relation as a chronicle is to reduce a sorting overhead during query processing. For instance, a traffic link time analysis requires time-ordered set of events reported by various PUs. An order-by query clause to establish order may induce unacceptably large sorting overhead at run time. Instead, sequencing has been performed already by each update transaction (insertion and merge operations) prior to such query, with only a small overhead imposed. As each PU will send data in a time sequence, only a merge process is required to maintain a chronicle in the database. Distributed database design is to make decisions on the optimal placement of data and programs across the sites of a computer network. The problem to address is to realize an efficient real-time distributed database processing, with primary emphasis on the temporal and spatial aspect of the data, that permits the management of the DBMS in each server pool and makes the

distribution transparent to the users. Queries over the stored sequence of transaction records have stringent response time requirements. Of particular interest are summary queries that access summation and aggregation information of traffic activity. One can think of the database configuration as decomposition of a relation into fragments, each being treated as fragmentation of relations typically results in the parallel execution of a single query by dividing it into a set of sub-queries that operate on fragments [24]. The query needs to build complete information from partial information.

A distributed chronicle instance is divided into chronicle fragments over the network. Distributed queries expressed on global schemas are mapped into queries on physical fragments of relations by translating relations into fragments. The aim of this research is to develop a set of optimal algorithms that exploit the chronicle fragments and supplemental information at run time to minimize communication overhead. The supplemental information must be built prior to the query in order to minimize data synchronization and to accelerate analysis computation. For instance, Figure 2 shows a set of data tuples representing the information of trucks 1, 2, and 3 (marked as t_1 , t_2 and t_3 , respectively) in the data chronicles maintained by the three Server Pools A, B and C. The tuple for t_1 spans Server Pools A and B; t_2 spans all three pools; t_3 is only found in Pool B. A summary computation must be made for analysis without gathering all these tuples into one place (i.e., without synchronizing all databases). Semi-join operation is often used to reduce the size of the operand relation and to reduce the size of data exchanged between the distributed servers. However, semi-joins are executed as queries, which may result in an increase in the number of messages and in the local processing time.

Alternatively, the computation starts with identifying the spanned data elements by exchanging the list of truck identifications and their frequencies found in the chronicles. These are incrementally built by update transactions, not by queries [25]. The information is sent to a coordinating server so that the decision will be made to which servers need to communicate to exchange tuples based on the frequencies. For example, as illustrated in Figure 3, Pool A needs to send t_1 to Pool B, Pool C needs to send t_1 to Pool A, and t_2 to Pool B. After the exchanges, the revised frequencies in the database will also be used for summary computations, which in turn eliminate counting aggregate computations.

3. SYSTEM INTEGRATION WITH VISTA

Extensive work has been performed for DTA-based traffic flow characteristics forecasting and vehicle routing. The DTA models rely on traffic simulators to emulate the traffic conditions especially for signalized systems where it is very difficult to capture the dynamics of traffic through analytical techniques. In general, simulation-based DTA models iterate between a traffic simulation module, a time-dependent shortest path module, and a network-loading module. First, given a set of vehicles and their travel paths, the traffic simulation module replicates complex traffic flow dynamics as the vehicles are propagated through the network. The link travel times reported by the simulator are then used to calculate the time dependent shortest paths. Those shortest paths are combined with all previous sets of shortest paths, and the vehicles are loaded onto the network on those paths. A new iteration then begins as the simulator propagates vehicles through

the network along the new combination of paths. The process stops when some user-specified convergence criterion is met.

3.1 VISTA Approach

The principal characteristics of VISTA [4] are: 1) the travelers' behavior is modeled using a Dynamic Traffic Assignment (DTA) model that reaches Dynamic User Equilibrium (DUE) at convergence 2) it utilizes a universal database model based on a spatial Geographic Information System (GIS) that can be easily interfaced with other databases; and 3) it is Internet and/or Intranet based, providing access to the various stakeholders to run the various algorithms, view the results of the models, query and change the database based on the authorization level of each.

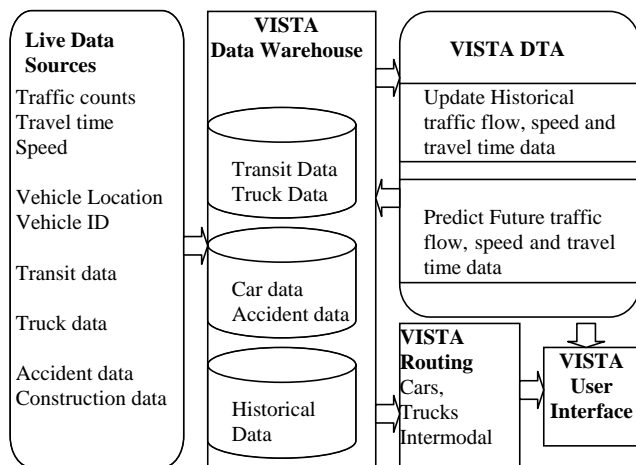


Figure 3 VISTA traffic flow characteristics forecasting.

The VISTA model's simulator, called RouteSim, uses cell transmission rules [26] for traffic propagation. In other words, the movements of small groups of vehicles are simulated as they enter and leave pre-defined cells. The simulator models bus and truck operations. A preliminary evaluation of transit signal priority was presented by the simulation capability in RouteSim [29].

The VISTA DTA model assigns each vehicle to a path based on the DUE rule. Under DUE, all vehicles for an OD pair are assigned to a set of paths that have equivalent travel time (cost) and the travelers cannot improve their travel time by changing their departure or arrival times. In addition, the VISTA-DTA model captures intermodal travelers and performs a person assignment that can be used to evaluate various transit related improvements such as bus/train schedules, transit stop locations, transit signal priority systems, and location of park and ride facilities. The VISTA system can generate automated traffic flow statistics at the network level, link, movement, and OD paths.. Furthermore, the system is flexible enough to allow the user to conduct parametric analyses by allowing only a percentage of vehicles to change their original paths. This is particularly useful in incident cases where only a set of users may have information about the incident and any alternative routes.

The main process of the implementation of a DTA model for real-time traffic flow forecasting is presented in Figure 3.

4. CONCLUSIONS

An integrated real-time traffic monitoring, distributed data model, communication model and traffic forecasting and vehicle routing

system are presented to improve the efficiency of a transport system while maintaining security through a redundant truck routing credential system. The principal innovations of the proposed system are:

- 1) A "flight path" for each commercial vehicle's origin to its destination. Throughout the trip, a truck and driver are monitored through a redundant set of fixed and mobile credential stations - for license, safety and security.
- 2) A simulation-based DTA traffic forecasting and vehicle routing system based on the "Rolling Horizon" concept - The DTA model is updated every few minutes based on real time traffic flow data.
- 3) An efficient real-time distributed data and communication system - from the traffic monitoring system to the operations center and the final stakeholders (transport and public agencies, emergency agencies, truck and transit operators, travelers, etc.).
- 4) An integrated transport and data/communication simulator that can be used to model all operations of the transport system.
- 5) A short and long term infrastructure asset management system that takes advantage of the integrated simulator to design the best configuration and maintenance of the transport system (roadway infrastructure, traffic control, traffic monitoring, commercial stations, communication, data processing).

The emerging discipline of computational transportation science has a transforming nature of the systems technology: from off-line transport models to real-time models and from non-integrated systems to integrated systems. The implementation of the systems integration proposed here is in progress: we plan to report on the performance analysis of the employed system.

5. ACKNOWLEDGMENTS

The authors thank research funds from Manhattan Borough President's Office, Silicon Graphics Inc., and Vista Transport Group.

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