A queue-based distributed traffic micro-simulation

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A Queue-Based Distributed Traffic Micro-Simulation

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Abstract

This Term Paper presents a distributed Traffic Micro-Simulation. The design goals were speed, realism, distributeability and simplicity. The speed goal was clearly achieved. As for the others, further work/testing is necessary.
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Chapter 1

Introduction

A bit of blabla about why we do traffic simulation and what it is good for

1.1 Design Concepts

The main goals set for the vsim Traffic Simulation were

- **Speed** The Simulation should run faster than existing programs.
- **Realism** The Simulation should be accurate enough to simulate even small traffic situations reliably.
- **Distributeability** The Simulation should be efficiently distributeable to take advantage of computer clusters.
- **Simplicity** The Simulation should be simple enough for anybody with basic computer science knowledge to extend.

To achieve this, a number of concepts were used, the most important four being:

- **Queue-Based Traffic Model** Provides a more realistic traffic model, where for each time-step the acceleration and not the displacement is calculated.
- **Multi-threaded Computer-Node Implementation** Takes advantage of multi-processor machines and amortizes time spent waiting on communication.
- **Explicit, Asynchronous Inter-Node Communication** Avoids overhead inherent to MPI and other libraries.
- **Multi-Constraint Graph Partitioning** Gives better graph partitions at the expense of more explicit node and street load data.

These four concepts and others will be explained in more detail further on.
Chapter 2

Traffic Model

As mentioned earlier, realism was one of the primary design goals. For the \texttt{vaim} Traffic Simulation, a classic particle simulation approach was taken where every car is aware of its position and speed and its acceleration is calculated and applied at every time-step.

Although this approach is more realistic, it is definitely more computationally intensive than cell-based models. Furthermore, this model also requires more network detail – i.e. definition of connectivity and priorities at nodes – which is not always available.

2.1 Cars

As mentioned earlier, the cars in \texttt{vaim} are aware of their position (depth into a street) and velocity. They have a route to follow, and a given start time. For added realism, each car also has a bias factor that influences its driving behavior – i.e. its tendency to speed and cut-off other vehicles.

Car acceleration is governed by a single procedure which, given an obstacle and its velocity, the car will calculate – knowing its own velocity – its acceleration for the next time-step.

Each car also decides on its own where and when to switch lanes, given information on if it has to or can switch lanes and the distances to and velocities of the cars ahead and behind on the neighboring lanes.

2.2 Streets

In \texttt{vaim}, streets are a collection of linked lists of cars, one for each lane. The streets are uni-directional and have therefore distinct from- and to-nodes.

In each time-step, all lanes are traversed in parallel from the from- to the to-end. Each car calculates its acceleration taking the car ahead of it as a moving obstacle. For the last car in each lane, the intersection is queried for distance and velocity on the destination street.
When a car leaves a street, it is passed over to the to-node which relays it to the next street in its route.

2.3 Intersections

Intersections in ViSim contain information about incoming and outgoing streets and about the way their lanes are interconnected, which connection has priority over which and which connections are activated in which time-steps (traffic lights).

In each time-step, a node calls on all incoming streets to move their cars. When it is queried by a street for a car to pass over, it first checks if there is a connection open for the car in question (lane and route defendant). If not, it will return an obstacle with distance and velocity 0. Otherwise, it queries the destination street (which can also be on a different computer) and returns the distance to and velocity of the first car there.
Chapter 3

Distributed Traffic Model

explain what changes have to be made and how these can affect the efficiency/reliability of the simulation.

3.1 Partitioned the Network

The network is partitioned by separating nodes and outgoing streets. A node with all its incoming streets can be seen as the smallest unit of computation. Communication is reduced to querying another computer only when a car passes over a node into a foreign street.

3.2 Vehicle Passing

The process of passing a car from one computer to the other consists of only two messages – a request and a response. For a node being queried, this looks as follows:
After sending a request, the node can remember the distance and velocity of the next obstacle returned by the other computer and so avoid multiple queries to the same street within the same time-step.

### 3.3 Coordination

The distributed simulation is controlled in a master/slave fashion. One machine (master) controls the others who actually run the simulation (slaves). The master can run on the same machine as a slave.

Once the simulation has been started in slave mode, it waits for a connection from a master. Once this connection is established, it receives information on where its input files resides and reads them. Once this has been done, it waits for a "tick" message, simulates one timestep and answers with either "ok" or "fail".

When running the simulation, the master sends out a "tick" to all slaves and waits until he has a response from all machines before continuing. A slave does not need to have received a "tick" before processing requests from other slaves.

Between timesteps the master can also request data, such as car positions and velocities or street travel times.
Chapter 4

Implementation

This chapter explains how the above mentioned traffic model was implemented for the vsim traffic simulation.

The program was entirely written in the C Programming Language.

4.1 Modules

Figure 4.1 shows the main modules in vsim and how they interact. Solid arrows denote interaction in the form of function calls, dashed arrows through network communication.

The modules runner, handler and msgr appear more than once, since various instances of those objects can be active at the same time in different threads.

The modules bcaster, car, route and model are missing from the diagram.

4.1.1 Traffic Modules

The modules that actual simulate traffic are node, street, car, route and model. As shown in Figure 4.2, the nodes, streets and routes are stored in

![Diagram of main modules and their interactions. Solid arrows denote communication in the form of function calls, dashed arrows through network communication.](image-url)
a btree in the main module vsim. The cars are stored directly in vsim as a linked list, sorted by their departure times.

The nodes, streets, cars and routes can be read by the functions node_read, street_read, car_read and route_read respectively. These functions take a file descriptor (FILE *) as an argument and return a pointer to a structure of the respective type or NULL if an error occurs.

These functions are called through the main module vsim through the functions vsim_readnodes, vsim_readstreets, vsim_readroutes and vsim_readcars respectively. All four procedures take the name of the file to be read (char *) as an argument and return the number of objects read (int) or a negative value if an error occurs.

The input functions in vsim must be called in the order given above for the objects to be linked together correctly.

Each time-step is initiated by either the command-line (module commline) or, in the case of a single slave in a distributed simulation, from the a network (module handler) by calling vsim_step. vsim_step first checks if any cars need to be inserted, then calls node_step on all nodes (how this is node in detail will be explained further in this text). node_step then calls street_step on each incoming street.

In the event of a car driving towards or over a node, street_step will call node_pass on its to_node with the car in question as an argument.

### 4.1.2 Communication Modules

As mentioned earlier, communication is done over TCP/IP using an explicit protocol. When not running in stand-alone mode, the main module (vsim)
initializes a **listener** and a **dispatcher** as shown in Figure 4.4.

The **listener**, once initialized, runs in its own thread and waits for connections on the port specified by the variable `vsim_port` in the module `vsim`. Once a connection is established, a new **handler** is created with the connection socket as an argument. The **handler** then reads messages from the given socket and processes them until program termination. If no messages are available, the **handler** waits.

The **dispatcher** handles requests for communication with a given IP-address (usual from a **node**) with the function `dispatcher_get`, returning a `msgr` to handle message passing. If no `msgr` exists for the given IP-address, a new one is created with `msgr_create`. Once the client is done communicating, the `msgr` is returned to the `dispatcher` with the function `dispatcher_put` without closing the network connection. The `msgr` can then be reused by any other thread requesting communication with the same IP-address.

### 4.1.3 Control Modules

As could be seen in Figure 4.2, `vsim` uses the modules **manager** and **runner**. When running in stand-alone or slave mode, the main module initializes a **manager** which, in turn, will create a given number of **runners** (the exact number is given by the constant `manager_numrunners`), each with their own thread, and gives each one a linked list of pointers to the nodes.

After being initialized, the **runners** wait at a barrier (`manager_wait`). At every time-step, the **manager** opens the barrier and waits. The **runners** then call `node_step` on each of the nodes in their list and reenter the barrier. Once all **runners** have finished, the **manager** is signaled and returns.

To guaranty an even load distribution between the **runners**, the **nodes** must be redistributed according to the time it takes to process them. The time spent on each **node** is measured every `runner_clockstep` seconds (since this implies a system call for every node, it is not done every time-step) and the **nodes** are redistributed every `manager_reschedule` seconds.

To avoid the hassle of redistribution, one could make all **runners** get their **nodes** from a common linked list. This however would require us to control access to this list (concurrency), which causes an enormous loss of performance on multi-processor machines.
4.1.4 Utility Modules

The only utility module used in the simulation is the btree module. This is a
generic, 16-way B-Tree with a 1024-entry cache of the last accessed members by
hash-value.

4.1.5 Other Modules

The conman module acts as a front end for a user in stand-alone or server
mode. After being initialized with conman_init, it reads commands from
standard input and delegates them to the vsim module. A description of the
commands can be found in Chapter 5.

The bcaster module is used by the simulation when running in server mode
and broadcasts messages to a number of clients. Clients can be added with
bcaster_add, yet only before connection is established with bcaster_open.
model

4.2 Functions and Data Structures

The following sections describe how the above mentioned modules were imple-
mented and what types, variables and functions are available.

4.2.1 bcaster

The bcaster's job is to maintain a number of connections to simulation clients
and broadcast commands and requests (i.e. for travel time data) to them.

<table>
<thead>
<tr>
<th>struct bcaster</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct conn conn[]</td>
</tr>
<tr>
<td>int nr_conns</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>struct conn</th>
</tr>
</thead>
<tbody>
<tr>
<td>int socket</td>
</tr>
<tr>
<td>unsigned int ip</td>
</tr>
</tbody>
</table>

int bcaster_init ( struct bcaster *b )
Initialize the given bcaster. On error, a negative value is returned.

int bcaster_add ( struct bcaster *b , unsigned int ip )
Add the given IP-address to the list of clients. This may only be done
before bcaster_open is called. On error, a negative value is returned.

int bcaster_remove ( struct bcaster *b , unsigned int ip )
Remove an IP-address from the list of clients. This may only be done
before bcaster_open is called. On error, a negative value is returned.
int bcaster_open ( struct bcaster *b )
Open connections to all clients. On error, a negative value is returned.

int bcaster_close ( struct bcaster *b )
Close connections to all clients. On error, a negative value is returned.

int bcaster_cast ( struct bcaster *b , char *msg , int msg_size , char *xpt , int xpt_size )
Cast the given message to all clients and compare the response to the given expected message. On error, or if a different response is given, a negative value is returned.

int bcaster_pos ( struct bcaster *b , FILE *out )
Ask all clients for their car positions and velocities and dump them to the given file. On error, a negative value is returned.

int bcaster_stime ( struct bcaster *b , FILE *out )
Ask all clients for the street travel times and dump them to the given file. On error, a negative value is returned.

4.2.2 btrees

The btrees are used to store nodes, streets and routes. It is generic in the sense that it can store any structure, as long as it starts with a unique integer value.

<table>
<thead>
<tr>
<th>struct btree</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct btree_node *first</td>
</tr>
<tr>
<td>struct btree_leaf *cache</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>struct btree_node</th>
</tr>
</thead>
<tbody>
<tr>
<td>int fill</td>
</tr>
<tr>
<td>int leaf</td>
</tr>
<tr>
<td>struct btree_leaf *cont[]</td>
</tr>
<tr>
<td>struct btree_node *nodes[]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>struct btree_leaf</th>
</tr>
</thead>
<tbody>
<tr>
<td>int key</td>
</tr>
</tbody>
</table>

struct btreen *btreenew ()

Create a new btree. On error, NULL is returned.

struct btreenode *btreefind ( struct btreen *t , int key )

Search for the element with the given key. On error, or if nothing is found, NULL is returned.

int btreeinsert ( struct btreen *t , struct btreenode *l )

Insert an element into the tree. On error, a negative value is returned.
int btreesap ( struct btree *t , int (*func)( struct btree_leaf * , void * ) , void *cont )
Apply the given function to all the elements in the btrees with the given argument. The applied function should return a negative value on error to interrupt execution. On error, a negative value is returned.

int btreescount ( struct btree *b )
Return the number of elements in this btrees. On error, a negative value is returned.

4.2.3 car
The car data structure contains data relative to the car state (position and velocity), as well as route and timing data. The next_step field is there for speed purposes only, as it could be locked up in the route. The end field is (mis)used for timing the car on each street.

<table>
<thead>
<tr>
<th>struct car</th>
</tr>
</thead>
<tbody>
<tr>
<td>int id</td>
</tr>
<tr>
<td>struct car *next</td>
</tr>
<tr>
<td>float length</td>
</tr>
<tr>
<td>float bias</td>
</tr>
<tr>
<td>float pos</td>
</tr>
<tr>
<td>float vel</td>
</tr>
<tr>
<td>int start , end</td>
</tr>
<tr>
<td>int step</td>
</tr>
<tr>
<td>int next_step</td>
</tr>
<tr>
<td>struct route *route</td>
</tr>
</tbody>
</table>

struct car *car_create ( int id , float length , float bias , int route_id , int start )
Create a car from with the given values. If the first street on the car’s route is not local, NULL is returned. On error, NULL is returned.

struct car *car_read ( FILE *in )
Read a car from the given file. If the first street on the car’s route is not local, NULL is returned. On error, NULL is returned.

struct car *car_rebuild ( int id , float length , float bias , int route_id , int start , int step )
Rebuild a car with the given values. This function is called by handler_pass. On error, NULL is returned.
4.2.4  commline

The commline reads commands from standard input, parses them and passes them on to the main module (vaim).

<table>
<thead>
<tr>
<th>struct commline</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>FILE *in</td>
<td>command line input</td>
</tr>
<tr>
<td>char *prompt</td>
<td>command line prompt</td>
</tr>
<tr>
<td>int nr_tokens</td>
<td>number of tokens in last line</td>
</tr>
<tr>
<td>struct token tokens[]</td>
<td>tokens from last line</td>
</tr>
</tbody>
</table>

int commline_init ( struct commline *c , FILE *in , char *prompt )
    Initialize the given commline with the given input file and prompt. On error, a negative value is returned.

int commline_run ( struct commline *c )
    Read and execute commands until the user terminates. On error, a negative value is returned.

4.2.5  dispatcher

The dispatcher manages a list of open connections to different clients as a hashtable over their IP-addresses.

<table>
<thead>
<tr>
<th>struct dispatcher</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>struct magr *magr[]</td>
<td>the mgrs</td>
</tr>
<tr>
<td>pthread_mutex *mutex</td>
<td>mutex for synchronising access to the mgr list</td>
</tr>
</tbody>
</table>

int dispatcher_init ( struct dispatcher *d )
    Initialize the given dispatcher. On error, a negative value is returned.

struct magr *dispatcher_get ( struct dispatcher *d , unsigned int ip )
    Get a mgr for the given IP-address. If none is available, a new one is created. On error, NULL is returned.

int dispatcher_put ( struct dispatcher *d , struct magr *m )
    Return a mgr to the dispatcher after use. On error, a negative value is returned.

4.2.6  error

The error module is used by all other modules and manages a stack of error messages which can be dumped or reset. In most modules, there is a macro error which maps to the function error_register with the appropriate message and LINE and FILE as parameters.
int error_register ( int id, char *msg, int line, char *file )
    Add a new error message to the stack. The parameter id is returned.

void error_dump ( FILE *out )
    Dump the error stack to the given file.

void error_reset ( )
    Reset the error stack.

4.2.7 handler
A handler, once created, runs in its own thread reading and processing commands from the network. Handlers are spawned by the listener.

<table>
<thead>
<tr>
<th>struct handler</th>
</tr>
</thead>
<tbody>
<tr>
<td>int socket</td>
</tr>
<tr>
<td>pthread_t thread</td>
</tr>
<tr>
<td>char buff[]</td>
</tr>
<tr>
<td>int bytes</td>
</tr>
</tbody>
</table>

struct handler *handler_create ( int socket )
    Create a new handler for the given socket. The handler will spawn its own thread and start receiving and processing commands. On error, NULL is returned.

int handler_kill ( struct handler *h )
    Tell the given handler to close its socket and terminate execution. On error, a negative value is returned.

4.2.8 listener
The listener runs in its own thread and waits for network connections on the port specified by vsis_port. Once a connection is received, it creates a new handler.

<table>
<thead>
<tr>
<th>struct listener</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct sockaddr_in addr</td>
</tr>
<tr>
<td>int sock</td>
</tr>
<tr>
<td>pthread_t thread</td>
</tr>
</tbody>
</table>

int listener_init ( struct listener *l )
    Initialize the given listener. This will also start it. On error, a negative value is returned.
4.2.9 manager

The manager handles control of the runners. Its main task is synchronizing
the runners and distributing the nodes over them evenly.

<table>
<thead>
<tr>
<th>struct manager</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct runner runners[]</td>
</tr>
<tr>
<td>struct node *nodes[]</td>
</tr>
<tr>
<td>int count</td>
</tr>
<tr>
<td>pthread_cond_t done_cond</td>
</tr>
<tr>
<td>pthread_mutex_t barrier_mutex</td>
</tr>
<tr>
<td>pthread_cond_t barrier_cond</td>
</tr>
</tbody>
</table>

int manager_init ( struct manager *m )
Initialize the given manager. On error, a negative value is returned.

int manager_wait ( struct manager *m )
Wait at the barrier. This function is called by the runners once they have finished processing their node-list. On error, a negative value is returned.

int manager_nodes ( struct manager *m )
Tell the manager to make a list of local nodes and distribute them over the runners. On error, a negative value is returned.

int manager_step ( struct manager *m )
Tell the manager to simulate one time-step by opening the barrier and waiting for all runners to return. On error, a negative value is returned.

4.2.10 model

The model module implements the driver behavior for each car. It has no data type, only three functions that govern acceleration and lane switching.

float model_drive ( float speed, float dist, float obst_speed, float bias, float limit )
Calculate the acceleration for a car driving at the given speed with an obstacle at dist meters with the given velocity. bias is the car-specific behavior value and limit is the speed limit on the current street.

int model_fit ( float speed, float bias, float dist_back, float vel_back, float dist_front, float vel_front )
Judges if the car will switch lanes or not, assuming it must. dist_back and vel_back refer to the first car behind on the lane to be switched to.
int model_pass ( float speed, float bias, float dist_front, float vel_front, float limit )

Decides if a car will switch lanes to pass the car with the given distance and velocity ahead of him, assuming his route allows it.

### 4.2.11 msgr

The msgr is in charge of communication with other machines in a distributed simulation.

<table>
<thead>
<tr>
<th>struct msgr</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct msgr *next</td>
</tr>
<tr>
<td>unsigned int ip</td>
</tr>
<tr>
<td>int socket</td>
</tr>
</tbody>
</table>

struct msgr *msgr_create ( unsigned int ip )

Create a new msgr and connect to the given IP-address. On error, NULL is returned.

int msgr_pass ( struct msgr *m, int street, struct car *c, float *dist, float *vel )

Attempt to pass the given car to the given street (in compressed form).

The position and velocity to the next obstacle on the street are written into *dist and *vel respectively. On error, a negative value is returned.

### 4.2.12 node

The module node represents a local intersection in the network. When reading nodes in a distributed simulation, the node module will return either a struct node or a struct node_foreign, depending on the node being on the current machine or elsewhere.
struct node

int id
unsigned int ip
float x_coord, y_coord
struct street *in[]
struct street *out[]
struct node *next
int nr_links
struct link links[]
int nr_steps
node_psktype sched[]
int curr_step
int decay

The compressed for for street/lane values can be decompressed with the functions street_getstreet and street_getlane and compressed with street_compact.

struct node *node_create ( int id , float x_coord , float y_coord ,
unsigned int ip )
Create a new node with the given values. On error, NULL is returned.

struct node *node_read ( FILE *in )
Read a node from the given file. This function may also return a node_foreign
if the node is not local. On error, NULL is returned.

struct node *node_read_noip ( FILE *in )
Read a node from the given file and assume that no IP-addresses have been
specified. This is used in stand-alone mode. On error, NULL is returned.

int node_step ( struct node *n )
Simulate one time-step on this node. On error, a negative value is returned.
int node_pass ( struct node *n, struct car *c, struct street *s, 
int lane, int to )
    Try to pass the car c from the given street and lane into the street/lane to 
in compressed format. Returns 1 if the car could be passed, 0 otherwise 
(negative on error). The car’s velocity and position are updated.

int link_read ( FILE *in )
    Read a link from the given file. This will update the affected nodes. On 
error, a negative value is returned.

int timing_read ( FILE *in )
    int phase_read ( FILE *in )
    int sign_read ( FILE *in )
    These functions read timing, phase and sign data for the nodes. This data 
is currently ignored by the simulation.

4.2.13 route

The route data structure is nothing more than a list of street ids. route.hoptype 
is defined either as an int or a short int. The id of last street in the route is 
-1.

<table>
<thead>
<tr>
<th>struct route</th>
</tr>
</thead>
<tbody>
<tr>
<td>int id</td>
</tr>
<tr>
<td>int nr_steps</td>
</tr>
<tr>
<td>route.hoptype step[]</td>
</tr>
</tbody>
</table>

struct route *route_create ( int id, int hops )
    Create a new route with the given number of hops. On error, NULL is 
returned.

struct route *route_read ( FILE *in )
    Read a route from the given file. On error, NULL is returned.

4.2.14 runner

A runner runs in its own thread and calls node_step on every node in its 
node-list every time-step.

<table>
<thead>
<tr>
<th>struct runner</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct manager *man</td>
</tr>
<tr>
<td>struct node *first</td>
</tr>
<tr>
<td>pthread_t thread</td>
</tr>
</tbody>
</table>

    the manager who controls this runner
    first node in this runner’s node-list
    the thread in which this runner is running

19
int runner_init ( struct runner *c , struct manager *m )
Initialize the given runner with the given manager. On error, a negative value is returned.

int runner_run ( struct runner *c )
Start the given runner. The runner will spawn its own thread and wait at the manager’s barrier until the next time-step. On error, a negative value is returned.

4.2.15 Street
The street data type describes a unidirectional street. As with the nodes, we distinguish between street and street_foreign.

<table>
<thead>
<tr>
<th>struct street</th>
</tr>
</thead>
<tbody>
<tr>
<td>int id</td>
</tr>
<tr>
<td>unsigned int ip</td>
</tr>
<tr>
<td>struct node *to, *from</td>
</tr>
<tr>
<td>struct lane *lanes[]</td>
</tr>
<tr>
<td>float length</td>
</tr>
<tr>
<td>float speed</td>
</tr>
<tr>
<td>pthread_mutex* mutex</td>
</tr>
<tr>
<td>int last_update</td>
</tr>
<tr>
<td>struct slot times[]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>struct street_foreign</th>
</tr>
</thead>
<tbody>
<tr>
<td>int id</td>
</tr>
<tr>
<td>unsigned int ip</td>
</tr>
<tr>
<td>struct node *to, *from</td>
</tr>
<tr>
<td>int nr_lanes</td>
</tr>
<tr>
<td>float dists[] , vels[]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>struct lane</th>
</tr>
</thead>
<tbody>
<tr>
<td>struct car *first, last</td>
</tr>
<tr>
<td>int exits[]</td>
</tr>
</tbody>
</table>
struct slot

<table>
<thead>
<tr>
<th>Field</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>int count</td>
<td>nr of cars that have passed through in this time-slot</td>
</tr>
<tr>
<td>int acc</td>
<td>accumulated time required by cars passing through in this time-slot</td>
</tr>
</tbody>
</table>

struct street *street_read ( FILE *in )
Read a street from the given file. This function can also return a street_foreign if the street is not local. On error, NULL is returned.

int street_step ( struct street *s )
Simulate one time-step on the given street. On error, a negative value is returned.

int lane_push ( struct street *s, struct lane *l, struct car *c )
Push the given car onto the given lane on the given street. This function is called by node_pass and by handler_pass. On error, a negative value is returned.

4.2.16 vsim

The vsim module is the main module in the simulation. It has no data types, but a number of variables and functions through which all operations and structures can be accessed.

struct btree *vsim_nodes
A btree containing all local and foreign nodes in the simulation.

struct btree *vsim_streets
A btree containing all local and foreign streets in the simulation.

struct btree *vsim_routes
A btree containing all routes in the simulation.

struct car *vsim_cars
A linked list of cars waiting to enter the simulation.

struct car *vsim_cars_out
A linked list of cars that have already left the simulation.

struct manager vsim_manager
The simulation manager.

struct listener vsim_listener
The simulation listener.

struct dispatcher vsim_dispatcher
The simulation dispatcher.
struct bcaster vsim_bcaster
   The simulation bcaster.

unsigned int vsim_ip
   The IP-address of the current machine.

int vsim_readnodes ( int with_ip , char *path )
   Read the nodes from the file with the given name. with_ip specifies if the
   IP-addresses of the nodes should be ignored or not. On error, a negative
   value is returned.

int vsim_readstreets ( char *path )
   Read the streets from the file with the given name. On error, a negative
   value is returned.

int vsim_readlinks ( char *path )
   Read the links from the file with the given name. On error, a negative
   value is returned.

int vsim_readsigns ( char *path )
   Read the signs from the file with the given name. On error, a negative
   value is returned.

int vsim_readroutes ( char *path )
   Read the routes from the file with the given name. On error, a negative
   value is returned.

int vsim_readcars ( char *path )
   Read the cars from the file with the given name. On error, a negative
   value is returned.

int vsim_step ( )
   Run the simulation through one time-step. On error, a negative value is
   returned.

int vsim_dump ( char *name )
   Dump the car positions and velocities to a file with the given name. On
   error, a negative value is returned.

int vsim_stimes ( char *name )
   Dump the street travel times to a file with the given name. On error, a
   negative value is returned.

### 4.3 Communication

Communication between machines in a distributed simulation consists, in most
cases, of a request with a single answer. The first byte in a message specifies
the message type. The message headers are stored in the handler module.
<table>
<thead>
<tr>
<th>Messages</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x0</td>
<td>error reply</td>
</tr>
<tr>
<td>0x1</td>
<td>ok reply</td>
</tr>
<tr>
<td>0x3 char= 0x0</td>
<td>read nodes from the given path, ok or error</td>
</tr>
<tr>
<td>0x4 char= 0x0</td>
<td>read streets from the given path, ok or error</td>
</tr>
<tr>
<td>0x5 char= 0x0</td>
<td>read links from the given path, ok or error</td>
</tr>
<tr>
<td>0x7 char= 0x0</td>
<td>read cars from the given path, ok or error</td>
</tr>
<tr>
<td>0x8 char= 0x0</td>
<td>read routes from the given path, ok or error</td>
</tr>
<tr>
<td>0x9 time[4]</td>
<td>set the simulation time to the given value in seconds, ok or fail as an answer</td>
</tr>
<tr>
<td>0xa</td>
<td>simulate one timestep (tick), ok or error as an answer</td>
</tr>
<tr>
<td>0xb street[4] length[4]</td>
<td>try to pass a car into the given street (compressed form with lane). the dist, vel, length and bias arguments are floats, the rest integers.</td>
</tr>
<tr>
<td>(0x10</td>
<td>0xc) dist[4] vel[4]</td>
</tr>
<tr>
<td>0xd</td>
<td>request street travel times</td>
</tr>
<tr>
<td>(id[4] (acc[4] count[4]))* 0x0</td>
<td>reply for street travel times. one message consists of the street id and the accumulated time and car count for each time slot.</td>
</tr>
<tr>
<td>0xef</td>
<td>request for car positions and velocities</td>
</tr>
</tbody>
</table>

4.4 Algorithms

Since most of the implementation is quite straight-forward, only a few interesting algorithms are presented here.

4.4.1 street_step

This is the function that simulates one time-step on a given street. Instead of processing one lane at a time and performing a linear search for lane neighbors, all the lanes are processed in parallel. Two arrays, prev and next, contain the
Figure 4.5: prev and next arrays for processing all lanes simultaneously

first and last cars in a sliding window over the street, making neighbor access a constant time operation (Figure 4.5, Algorithm 1).

4.4.2 node.pass
The node.pass algorithm (Algorithm 2) decides if a car can cross a node and if so, delegates the car to the appropriate street — local or foreign.

4.5 File Formats
The vensim Traffic Simulation uses, with some exceptions, the same file formats as the TRANSIMS Traffic Simulation. It is however possible to convert the differing formats from one program to the other with the help of some small scripts.

4.5.1 Nodes
The nodes-file is identical to that of TRANSIMS with one small detail: if the simulation is to run in a distributed way, then the IP-address of the machine where the node is to reside must be added to the "NOTES" column as an unsigned integer.
Algorithm 1: street_step

fill prev array with NULL
fill next array with first car in each lane

while next not empty do
    current = car with smallest pos in next
    pos = lane nr. of current
    next[pos] = current->next

    if current has a next street and this lane does not exit on that street then
        if switching to the right will get me where i want to go and i have enough room to switch lanes then
            prev[pos]->next = next[pos]
            current->next = next[pos - 1]
            prev[pos - 1]->next = current
        else if switching to the left will get me where i want to go and i have enough room to switch lanes then
            prev[pos]->next = next[pos]
            current->next = next[pos + 1]
            prev[pos + 1]->next = current
        end if
    else if i have a lane to my right where i fit then
            prev[pos]->next = next[pos]
            current->next = next[pos - 1]
            prev[pos - 1]->next = current
        end if

    if current must leave the simulation and current->pos > half the street length then
            prev[pos]->next = next[pos]
            vsim_out(current)
        else
            if current has a car in front then
                accel = model_drive(...)
                current->pos += current->vel + accel * 0.5
                current->vel += accel
                prev[pos] = current
            else
                if node_pass(...) == 1 then
                    prev[pos]->next = current->next
                else
                    prev[pos] = current
                end if
            end if
        end if
    end while
\textbf{Algorithm 2} node\_pass

\textbf{Require}: car \( c \), street/lane \( \text{from} \), street/lane \( \text{to} \)
if no link from \( \text{from} \) to \( \text{to} \) or
link has unfulfilled wait or halt condition then
\hspace*{1em} \text{accel} = \text{model\_drive}(\ldots) \{ \text{act as if node were a dead end} \}
\hspace*{1em} \text{return } 0
\hspace*{1em} end if

if \( \text{to} \) is local then
\hspace*{1em} \text{accel} = \text{model\_drive}(\ldots) \{ \text{next obstacle is first car on } \text{to} \}
\hspace*{1em} \text{c}\_\text{pos} \leftarrow \text{c}\_\text{vel} + \text{accel} \times 0.5
\hspace*{1em} \text{c}\_\text{vel} \leftarrow \text{accel}

\hspace*{1em} \{ \text{did the car cross over the node?} \}
if \( \text{c}\_\text{pos} > \text{from}\_\text{length} \) then
\hspace*{1em} \text{c}\_\text{pos} \leftarrow \text{from}\_\text{length}
\hspace*{1em} \text{lane\_push}(\text{to}, \text{c})
\hspace*{1em} \text{return } 1
else
\hspace*{1em} \text{return } 0
end if
else
\hspace*{1em} \text{mgr} = \text{dispatcher\_get}(\text{to}\_\text{ip})
\hspace*{1em} \text{dist} = \text{from}\_\text{length} - \text{c}\_\text{pos}
\hspace*{1em} \text{vel} = \text{c}\_\text{vel}

\hspace*{1em} \{ \text{does the car leave us?} \}
if \text{mgr\_pass(mgr.to,c.dist,vel)} \leftarrow 0 \text{ then}
\hspace*{1em} \text{accel} = \text{model\_drive}(\ldots) \{ \text{use dist and vel as next obstacle} \}
\hspace*{1em} \text{c}\_\text{pos} \leftarrow \text{c}\_\text{vel} + \text{accel} \times 0.5
\hspace*{1em} \text{c}\_\text{vel} \leftarrow \text{accel}
\hspace*{1em} \text{return } 0
else
\hspace*{1em} \text{free } \text{c}
\hspace*{1em} \text{return } 1
end if
end if
4.5.2 Cars and Routes

The cars- and routes-files used in the vrais Traffic Simulation depart from the TRANSIMS plans-format completely.

The cars-file contains a list with three entries: the car id, its start time in seconds and the id of the route to take. The route-file contains a list of routes specified by id, number of steps and the steps themselves. The route steps are node ids.

<table>
<thead>
<tr>
<th>cars-file</th>
</tr>
</thead>
<tbody>
<tr>
<td>car id</td>
</tr>
<tr>
<td>start time</td>
</tr>
<tr>
<td>route id</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>routes-file</th>
</tr>
</thead>
<tbody>
<tr>
<td>route id</td>
</tr>
<tr>
<td>nr steps</td>
</tr>
<tr>
<td>steps*</td>
</tr>
</tbody>
</table>

4.5.3 Street Travel Times

The vrais Traffic Simulation can generate a file containing information on street usage. The file has one line per street and contains the number of cars and the sum of their travel times per time-slot. The number of time-slots per day is defined in the variable street_slotsize.

<table>
<thead>
<tr>
<th>street travel times</th>
</tr>
</thead>
<tbody>
<tr>
<td>street id</td>
</tr>
<tr>
<td>[count, total time]*</td>
</tr>
</tbody>
</table>
Chapter 5

vsim – The Traffic Simulation

This chapter describes how to use the vsim Traffic Simulation in its different modes and presents some results obtained with the implementation described here.

The vsim Traffic Simulation is started with the command ./vsim. out and accepts the following command-line arguments:

<table>
<thead>
<tr>
<th>command-line arguments</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>-l path</td>
<td>use path as the default path</td>
</tr>
<tr>
<td>-n file</td>
<td>use file as the default node-file</td>
</tr>
<tr>
<td>-s file</td>
<td>use file as the default street-file</td>
</tr>
<tr>
<td>-r file</td>
<td>use file as the default route-file</td>
</tr>
<tr>
<td>-c file</td>
<td>use file as the default car-file</td>
</tr>
<tr>
<td>-l file</td>
<td>use file as the default link-file</td>
</tr>
<tr>
<td>-i ip</td>
<td>set the IP-address to ip</td>
</tr>
<tr>
<td>-m mode</td>
<td>set the mode in which to run. mode must be one of standalone, server or client. standalone is the default.</td>
</tr>
</tbody>
</table>

If you started in stand-alone or server mode, you will get a command prompt from which you can control the simulation. The commands are described in the following sections.

5.1 Running in Stand-Alone Mode

When running in stand-alone mode, the -i parameter will have no effect. Neither will any IP-addresses in the node-file.
### stand-alone mode

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><code>time</code></td>
<td>print the current simulation time</td>
</tr>
<tr>
<td><code>time int</code></td>
<td>set the current time to <code>int</code> seconds</td>
</tr>
<tr>
<td><code>step</code></td>
<td>simulate one timestep</td>
</tr>
<tr>
<td><code>step int</code></td>
<td>simulate <code>int</code> timesteps</td>
</tr>
<tr>
<td><code>view</code></td>
<td>open or update the viewer</td>
</tr>
<tr>
<td><code>view int</code></td>
<td>update the view every <code>int</code> seconds</td>
</tr>
<tr>
<td><code>prefix</code></td>
<td>print the prefix used for all files</td>
</tr>
<tr>
<td><code>prefix &quot;path&quot;</code></td>
<td>set the file prefix to <code>path</code></td>
</tr>
<tr>
<td><code>nodes</code></td>
<td>load the nodes from the default file</td>
</tr>
<tr>
<td><code>nodes &quot;file&quot;</code></td>
<td>load the nodes from <code>file</code></td>
</tr>
<tr>
<td><code>streets</code></td>
<td>load the streets from the default file</td>
</tr>
<tr>
<td><code>streets &quot;file&quot;</code></td>
<td>load the streets from <code>file</code></td>
</tr>
<tr>
<td><code>cars</code></td>
<td>load the cars from the default file</td>
</tr>
<tr>
<td><code>cars &quot;file&quot;</code></td>
<td>load the cars from <code>file</code></td>
</tr>
<tr>
<td><code>routes</code></td>
<td>load the routes from the default file</td>
</tr>
<tr>
<td><code>routes &quot;file&quot;</code></td>
<td>load the routes from <code>file</code></td>
</tr>
<tr>
<td><code>count</code></td>
<td>print the nr of cars currently in the simulation</td>
</tr>
<tr>
<td><code>dump</code></td>
<td>dump the car positions and velocities to a file in a TRANSIMS-compatible format with an automatically generated name (&quot;dump/vsim.[time].dump&quot;).</td>
</tr>
<tr>
<td><code>dump &quot;file&quot;</code></td>
<td>dump the car positions and velocities into <code>file</code></td>
</tr>
<tr>
<td><code>dump int</code></td>
<td>automatically dump car positions and velocities every <code>int</code> seconds</td>
</tr>
<tr>
<td><code>stimes &quot;file&quot;</code></td>
<td>dump the street travel times into <code>file</code></td>
</tr>
<tr>
<td><code>quit</code></td>
<td>don't know – the program keeps shutting down when I do this...</td>
</tr>
</tbody>
</table>

A typical simulation session will look as follows:

```
vsim - distributed traffic simulation
(c) 2001 by pedro gonnet (pedro@vis.ethz.ch)
vsim_standalone: running in standalone-mode...

[vsim_standalone] prefix "files/
command: current directory set to files/

[vsim_standalone] nodes
command: read 10564 nodes from file nodes.data.

[vsim_standalone] streets
command: read 28622 streets from file streets.data.

[vsim_standalone] routes
```
comline: read 49980 routes from file files/routes.data.

[vsim_standalone] cars
comline: read 49980 cars from file files/cars.data.

[vsim_standalone] time 21600
comline: current time set to 06:00:00 (21600s)

[vsim_standalone] dump 600
comline: dumpstep set to 600.

[vsim_standalone] step 3600
comline: 344 seconds elapsed (10.47 ratio)...

[vsim_standalone] view

[vsim_standalone] quit

The session tells the simulation where to look for its file (prefix "files/"), reads first the nodes, then the streets, routes and cars. This order must always be observed for the simulation to work. The time is then set to 06.00 (time 21600). The simulation is told to produce dumps every 600 seconds (dump 600) and is let run for one hour (step 3600). Finally, a viewer is opened and the simulation is quit.

5.2 Running in Server Mode

To run the vsim Traffic Simulation in server mode, one must first create a node-file with the IP-addresses of all client machines. Furthermore, the vsim Traffic Simulation must be running in client mode on all client machines with the -i flag specifying the IP-address.
server mode

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>client &quot;ip&quot;</td>
<td>adds a client with the IP-address ip in dot notation</td>
</tr>
<tr>
<td>connect</td>
<td>connects to all clients</td>
</tr>
<tr>
<td>disconnect</td>
<td>close all open connections to clients</td>
</tr>
<tr>
<td>time</td>
<td>print the current simulation time</td>
</tr>
<tr>
<td>time int</td>
<td>set the current time to int seconds</td>
</tr>
<tr>
<td>step</td>
<td>simulate one timestep</td>
</tr>
<tr>
<td>step int</td>
<td>simulate int timesteps</td>
</tr>
<tr>
<td>prefix</td>
<td>print the prefix used for all files</td>
</tr>
<tr>
<td>prefix &quot;path&quot;</td>
<td>set the file prefix to path</td>
</tr>
<tr>
<td>nodes</td>
<td>load the nodes from the default file</td>
</tr>
<tr>
<td>nodes &quot;file&quot;</td>
<td>load the nodes from file</td>
</tr>
<tr>
<td>streets</td>
<td>load the streets from the default file</td>
</tr>
<tr>
<td>streets &quot;file&quot;</td>
<td>load the streets from file</td>
</tr>
<tr>
<td>cars</td>
<td>load the cars from the default file</td>
</tr>
<tr>
<td>cars &quot;file&quot;</td>
<td>load the cars from file</td>
</tr>
<tr>
<td>routes</td>
<td>load the routes from the default file</td>
</tr>
<tr>
<td>routes &quot;file&quot;</td>
<td>load the routes from file</td>
</tr>
<tr>
<td>count</td>
<td>print the nr of cars currently in the simulation</td>
</tr>
<tr>
<td>dump</td>
<td>dump the car positions and velocities to a file in a TRANSIMS-compatible format with an automatically generated name (&quot;dump/vsim.[time].dump&quot;).</td>
</tr>
<tr>
<td>dump &quot;file&quot;</td>
<td>dump the car positions and velocities int file</td>
</tr>
<tr>
<td>dump int</td>
<td>automatically dump car positions and velocities all int seconds</td>
</tr>
<tr>
<td>stimes &quot;file&quot;</td>
<td>dump the street travel times into file</td>
</tr>
<tr>
<td>quit</td>
<td>don’t know – the program keeps shutting down when I do this...</td>
</tr>
</tbody>
</table>

A typical session would look like a normal stand-alone session, yet with a few client lines and a connect at the beginning.

### 5.3 Running in Client Mode

Running the vsim Traffic Simulation in client mode is trivial, since there is no direct interaction with the user. The simulation must be started with the -i parameter specifying the IP-address through which the machine will be called.
Chapter 6

Performance Results

The traffic simulation was tested with two different traffic scenarios:

- **Gotthard Scenario**: 50,000 cars trying to cross the Swiss Alps. The cars start between 06:00 and 07:00, get stuck at the Gotthard tunnel until about 06:00 the next day.

- **Switzerland Scenario**: 6,000,000 cars travelling in, out and around Switzerland. Traffic starts at 00:00 and accumulates until about 21:00 and disperses two days later. This scenario was designed as a stress test for large-scale microsimulations.

Both simulations use a traffic network consisting of 10,564 nodes and 28,622 streets. The network represents a rough roadmap of Europe with more detail in Switzerland.

The distributed tests were run on the Institute of Computer Systems’ CoPs Cluster [CoPs] consisting of 16 dual-Pentium III 1GHz machines with switched gigabit ethernet.

6.1 Gotthard Scenario

The simulation was run on only 8 machines in the CoPs cluster. This was not for performance reasons, but more due to the fact that the whole cluster could only be reserved over the weekend and not all tests could be run on time.

Furthermore, the simulation was run using 10 runners. The exact number is rather arbitrary, but it produced better results than 5 or 20 threads.

The results are summed up as simulated seconds per wall-clock seconds over six hour timespans.
6.2 Switzerland Scenario

For this simulation, all 16 machines were used, each running 5 threads. As with the last scenario, the simulation time / real time ratio was measured for six hour time intervals.

<table>
<thead>
<tr>
<th>Switzerland Scenario</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>00:00 – 06:00</td>
<td>136.71 s/s</td>
</tr>
<tr>
<td>06:00 – 12:00</td>
<td>67.71 s/s</td>
</tr>
<tr>
<td>12:00 – 18:00</td>
<td>52.94 s/s</td>
</tr>
<tr>
<td>18:00 – 24:00</td>
<td>41.54 s/s</td>
</tr>
<tr>
<td>geom. avg.</td>
<td>67.17 s/s</td>
</tr>
</tbody>
</table>

6.3 Notes

6.3.1 Graph Partitioning

One of the greatest speedup factors was, without doubt, the partitioning of the traffic network. This was done with the METIS graph partitioning package [MET].

The input for the graph partitioning was generated from the street travel times data collected after one simulation run. For each time-slot, a node is

---

Figure 6.1: Multi-Constraint Partitioning: The values in square brackets for each node denote the load over two different time-slots. If the average load over both time-slots is considered, then both partitions (green and red) are equally good. Yet if we consider both loads separately, the green partitioning is far better than the red.

---
assigned the sum of the accumulated travel times in seconds for each incoming street (i.e. the number of car-seconds it has to process). The streets are weighted by the number of cars that entered the street per time-slot (i.e. the number of transactions necessary if we were to cut that street).

For both simulations partitions were created using the data from eight time-slots as multiple constraints. This produced much better results than the partitioning used by TRANSIMS which divides the network according to one set of constraints. Figure 6.1 shows how and why this can go wrong.

6.3.2 Threads

It is rather difficult to quantify the number of threads needed for a given simulation. The overhead involved in task-switching has to be less than time spent on un-amortized communication.

For both scenarios, the best numbers of runners was calculated experimentally.

6.3.3 Useability

Although the speed results of the vsim Traffic Simulation are rather impressive, the results produced are completely useless. Since no information on street priorities or traffic lights were available for the network, the realism of the traffic model quickly became a major drawback, creating pileups at almost every unsignalized crossing.

There are many ways this could be fixed, yet defining a better network would be preferable.
Chapter 7

Outlook

7.1 What has been done

The best way to quantify what has been achieved is to compare the end results with the design goals mentioned at the beginning of this text.

7.1.1 Speed

The speed criteria is probably the easiest to quantify, since the results can be measured and compared. Since no reference numbers were available for either one of the scenarios tested, there is no direct comparison to previous work.

The only reference available is the theoretical limit of 100 simulated seconds per second with a similar cluster configuration postulated in [ParTS] for the parallel implementation of the TRANSIMS micro-simulation.

7.1.2 Realism

As mentioned earlier, the results of the vsim Traffic Simulation are completely unusable. The question, whether this is a problem with the simulation itself or the network, would require running the simulation on a more complete network.

7.1.3 Distributeability

The vsim Traffic Simulation is easily distributeable and the distributed traffic model seems works. No real analysis was made of the usage of network resources or on the amount of time waiting on I/O, making it difficult to make a concrete statement.

7.1.4 Simplicity

The whole source of the vsim Traffic Simulation is less than 6000 lines of c-code. The modularity of the system allows the user to modify parts of the
system without needing to be completely familiar with the rest. The separation of the model module should be especially useful for those testing new driver behaviour models.

7.2 What has not yet been done

There are still a number of features that were originally planned, yet not yet implemented into the vSim Traffic Simulation. Since the simulation was designed assuming their existence, it should be possible to add them without too many problems.

7.2.1 Signaled Intersections

Although the node module can read intersection data, it is not regarded in node.pass. One big problem here would be how to handle yellow phases. The easiest solution would be to add one function to the model module which decides if to pass or brake.

7.2.2 Wait and Halt Conditions

This information is read but not used by node.pass. There are comments in the source indicating where to insert eventual code. Unfortunately, the information in the TRANSIMS files only tells us where a stop or yield sign stands, and not which lanes or links it pertains to.
Bibliography

[CoPs] Research Group for Parallel and Distributed Systems – Cluster
http://www.cs.inf.ethz.ch/stricker/lab/

[MET] METIS: Serial Graph/Mesh Partitioning & Sparse Matrix Ordering
http://www-users.cs.umn.edu/~karypis/metis/metis/

[ParTS] Parallel implementation of the TRANSIMS micro-simulation.
Kai Nagel and Marcus Rickert