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Fuzzy Ramp Implementation

**A Programmer's Guide to the
Fuzzy Logic Ramp Metering Algorithm:
Software Design, Integration, Testing, and
Evaluation**

by

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INTRODUCTION

This report documents the implementation of the Fuzzy Logic Ramp Metering Algorithm at the Northwest District of the Washington State Department of Transportation (WSDOT). The preliminary stages of the software documentation and the software integration plan were carried out under a previous WSDOT/TransNow research grant. For documentation of the pre-existing code that now interfaces with the Fuzzy Logic Ramp Metering Algorithm, see Taylor and Meldrum, 1997.

Three reports represent the culmination of the Fuzzy Logic Ramp Metering Algorithm project. 1) This programmer's guide contains the software design for the new and modified code, the integration procedure, the results of software regression testing, the test results of new functionality, a discussion of the performance evaluation software used, the algorithm's transferability to other regions, and recommendations for the future. 2) See "Evaluation of a Fuzzy Logic Ramp Metering Algorithm: A Comparative Study Among Three Ramp Metering Algorithms used in the Greater Seattle Area" for the research approach, evaluation method, and the on-line test results of the Fuzzy Logic Ramp Metering Algorithm (Taylor and Meldrum, 2000). 3) For information regarding the algorithm design and tuning technique, see the technical report "Algorithm Design, User Interface, and Optimization Procedure for a Fuzzy Logic Ramp Metering Algorithm: A Training Manual for Freeway Operations Engineers" (Taylor and Meldrum, 2000).

SOFTWARE DESIGN

The Fuzzy Logic Ramp Metering Algorithm was implemented in a manner parallel to the other processes within the Transportation Management Software (TMS). Fuzzy metering is implemented as the last Traffic Analysis Program (TAP) before the Real Time Data Base (RTDB) is scrolled. All TAPS read an input file created during the database build. In the case of fuzzymeter, it reads “fuzzy_meter.eqn” produced by running build_rmdb. All TAPS execute their calculations every 20 seconds when rt_skeleton sets their particular start flag. As soon as the rt_skeleton receives the flag that a TAP has completed or timed-out (whichever comes first), rt_skeleton will begin the next process.

Watch_fuzzymeter was implemented as a utility in a manner parallel to the other stand-alone utilities. It updates the display of the fuzzymeter calculations every 20 seconds when it is called from rt_skeleton. It is called from rt_skeleton after the other watch utilities have completed. (The TAPS are executed before the RTDB is scrolled, and the utilities are executed after the RTDB has been scrolled.)

All modified and new code contains internal documentation in the source code, which is more detailed than that given here. This report contains supplementary documentation to provide an overview of the software design. For the psuedo code given, the bulleted level of indentation refers to the software control structure. Module names are in boldface. Defined constants are in all capital letters.

MODIFIED CODE

The Fuzzy Logic Ramp Metering Algorithm interfaces with the Ramp Metering Data Base (RMDB), real-time skeleton, operator console, and 170s. Through the RMDB, the user can specify the inputs for each metered lane and define the control parameter defaults. The real-time skeleton executes all real-time processes at the appropriate time. Through the operator console, the operators can monitor and adjust the Fuzzy Logic Ramp Metering Algorithm. With changes to `rmdb_comm`, `fuzzymeter` can send its metering rates to the 170s. All total, approximately 77,000 lines of code were modified to integrate the algorithm. These modifications were for the controller interface (not the controller itself) and are specific to Seattle's TSMC.

Ramp Metering Database

To incorporate the fuzzy ramp metering algorithm, additional global parameters were added to the RMDB. New fuzzy metering parameters allow the operators to enable and tune the algorithm. The resulting fuzzy metering rates are written to new elements in RMDB. To add these new elements to the RMDB, changes to the RMDB were made in `rmdb.h` and `rmdb_tbl.c`. To parse the new fuzzy parameters and fuzzy equations in the input file, modifications were made to `build_rmdb.c`, `rmdb_sub.c`, and `tok_tbl.c`. The prototypes for the new functions to parse the fuzzy equations were added to `rmdb_func_prot.h`. This section describes in detail the changes made to each file and the pseudo code for the new functions. Table 2 summarizes the modifications for each file related to the RMDB.

Changes to `rmdb.h`

- 1) Define indices for two new group names

```
#define FUZZYMETER_PARAMS      20
```

#define FUZZYMETER_EQNS 21

- 2) Modify the structure `rmdb_file_pointers` (structure `rmdb_table_list` points to this table as well as other tables) to include a FILE pointer for `fuzzy_meter.eqn`. This is for the temporary equation file created by `build_rmdb` and used by `fuzzymeter` to build the fuzzy table.
- 3) Modify the structure for `rm_dc_data_col` to include the three new 170_Data parameters, `_MeterRateLane1`, `_MeterRateLane2` and `_MeterRateLane3`, which store the resulting fuzzy logic ramp metering rates for each lane.
- 4) Modify the structure for `rm_dc_data_col` to include the 52 new `Fuzzy_Meter_Parameters` that include dynamic range limits, rule weights, operator permit fuzzy control. The parameter specifications are given in Table 1.
- 5) Change defined indices to enumerated constants. (The values are equivalent.)

Changes to `rmdb_tbl.c`

- 1) Add the two new group names `Fuzzymeter_Parameters` and `Fuzzymeter_Equations` to the `group_table` array. This array is of the structure `fddb_group_table`, defined in `fddb.h`. The structure itself does not need modification. This array must correspond to the group name indices defined in `rmdb.h`.
- 2) Modify the `minimum`, `maximum`, `default`, and `ep_mask` arrays to include initial values for the new parameters (See Table 1). These arrays are of structure type `rm_dc_data_col` defined in `rmdb.h`. The arrays must fit this structure.
- 3) Add new parameters to the `name_table`. This array is of type `fddb_name_table`, which is defined in `fddb.h`. The structure itself does not need modification. This array must correspond with parameter structure for data column in `rmdb.h`.

- 4) Add new group names and element names to output_list array. This array is of the structure fddb_output_list, defined in fddb.h. The structure itself does not need modification. The output list must correspond with the parameter structure and group indices defined in rmdb.h.

Table 1. Fuzzy Metering Parameters

NAME	DESCRIPTION	CODING	UNIT	MIN	MAX	DEFAULT	EXAMPLE
AdvQueueOccHigh1	High end of dynamic range for Advance Queue Occ, lane 1	USHORT1P	%	0.0%	100.0%	30.0%	AdvQueueOccHigh1 = 30.0%
AdvQueueOccHigh2	High end of dynamic range for Advance Queue Occ, lane 2	USHORT1P	%	0.0%	100.0%	30.0%	AdvQueueOccHigh2 = 30.0%
AdvQueueOccHigh3	High end of dynamic range for Advance Queue Occ, lane 3	USHORT1P	%	0.0%	100.0%	30.0%	AdvQueueOccHigh3 = 30.0%
AdvQueueOccLow1	Low end of dynamic range for Advance Queue Occ, lane 1	USHORT1P	%	0.0%	100.0%	12.0%	AdvQueueOccLow1 = 12.0%
AdvQueueOccLow2	Low end of dynamic range for Advance Queue Occ, lane 2	USHORT1P	%	0.0%	100.0%	12.0%	AdvQueueOccLow2 = 12.0%
AdvQueueOccLow3	Low end of dynamic range for Advance Queue Occ, lane 3	USHORT1P	%	0.0%	100.0%	12.0%	AdvQueueOccLow3 = 12.0%
AdvQueueOccWt1	Weight for Adv Queue Occupancy Rule, lane 1	UBYTE1	N/A	0.0	25.5	4.0	AdvQueueOccWt1 = 4.0
AdvQueueOccWt2	Weight for Adv Queue Occupancy Rule, lane 2	UBYTE1	N/A	0.0	25.5	4.0	AdvQueueOccWt2 = 4.0
AdvQueueOccWt3	Weight for Adv Queue Occupancy Rule, lane 3	UBYTE1	N/A	0.0	25.5	4.0	AdvQueueOccWt3 = 4.0
DownOccHigh	High end of dynamic range for Downstream Occupancy	USHORT1P	%	0.0%	100.0%	25.0%	DownOccHigh = 25.0%
DownOccLow	Low end of dynamic range for Downstream Occupancy	USHORT1P	%	0.0%	100.0%	11.0%	DownOccLow = 11.0%
DownSpeedHigh	High end of dynamic range for Downstream Speed	USHORT1	MPH	0.0	100.0	55.0	DownSpeedHigh = 55.0
DownSpeedLow	Low end of dynamic range for Downstream Speed	USHORT1	MPH	0.0	100.0	40.0	DownSpeedLow = 40.0
DownSpVs_OccVbWt	Weight for Very Small Speed and Very Big Occ Rule	UBYTE1	N/A	0.0	25.5	4.0	DownSpVs_OccVbWt= 4.0

NAME	DESCRIPTION	CODING	UNIT	MIN	MAX	DEFAULT	EXAMPLE
LocalOccHigh	High end of dynamic range for Local Occupancy	USHORT1P	%	0.0%	100.0%	25.0%	LocalOccHigh = 25.0%
LocalOccLow	Low end of dynamic range for Local Occupancy	USHORT1P	%	0.0%	100.0%	11.0%	LocalOccLow = 11.0%
LocalOccVbWt	Weight for Local Very Big Occupancy Rule	UBYTE1	N/A	0.1	25.5	2.5	LocalOccVbWt = 2.5
LocalOccBWt	Weight for Local Big Occupancy Rule	UBYTE1	N/A	0.1	25.5	1.0	LocalOccBWt = 1.0
LocalOccMWt	Weight for Local Medium Occupancy Rule	UBYTE1	N/A	0.1	25.5	1.0	LocalOccMWt = 1.0
LocalOccSWt	Weight for Local Small Occupancy Rule	UBYTE1	N/A	0.1	25.5	1.0	LocalOccSWt = 1.0
LocalOccVsWt	Weight for Local Very Small Occupancy Rule	UBYTE1	N/A	0.1	25.5	1.0	LocalOccVsWt = 1.0
LocalSpeedHigh	High end of dynamic range for Local Speed	USHORT1	MPH	0.0	100.0	55.0	LocalSpeedHigh = 55.0
LocalSpeedLow	Low end of dynamic range for Local Speed	USHORT1	MPH	0.0	100.0	35.0	LocalSpeedLow = 35.0
LocSpVs_OccVbWt	Weight for Local Very Small Speed and Very Big Occ Rule	UBYTE1	N/A	0.0	25.5	3.0	LocSpVs_OccVbWt = 3.0
LocalSpeedSWt	Weight for Local Small Speed Rule	UBYTE1	N/A	0.0	25.5	1.0	LocalSpeedSWt = 1.0
LocalSpeedBWt	Weight for Local Big Speed	UBYTE1	N/A	0.0	25.5	1.0	LocalSpeedBWt = 1.0
LocSpVb_OccVsWt	Weight for Local Very Big Speed and Very Small Occ Rule	UBYTE1	N/A	0.0	25.5	1.0	LocSpVb_OccVsWt = 1.0
MeterRateHigh1	High limit for metering rate produced by fuzzy controller, lane 1	UBYTE1	VPM	0.0	25.5	19.3	MeterRateHigh1 = 19.3
MeterRateHigh2	High limit for metering rate produced by fuzzy controller, lane 2	UBYTE1	VPM	0.0	25.5	19.3	MeterRateHigh2 = 19.3
MeterRateHigh3	High limit for metering rate produced by fuzzy controller, lane 3	UBYTE1	VPM	0.0	25.5	19.3	MeterRateHigh3 = 19.3

NAME	DESCRIPTION	CODING	UNIT	MIN	MAX	DEFAULT	EXAMPLE
MeterRateLow1	Low limit for metering rate produced by fuzzy controller, lane 1	UBYTE1	VPM	0.0	25.5	3.0	MeterRateLow1 = 3.0
MeterRateLow2	Low limit for metering rate produced by fuzzy controller, lane 2	UBYTE1	VPM	0.0	25.5	3.0	MeterRateLow2 = 3.0
MeterRateLow3	Low limit for metering rate produced by fuzzy controller, lane 3	UBYTE1	VPM	0.0	25.5	3.0	MeterRateLow3 = 3.0
PermitFuzzyMr1	Enable fuzzy control at this meter	YES_NO	FLAG	NO	YES	NO	PermitFuzzyMr1 = NO
PermitFuzzyMr2	Enable fuzzy control at this meter	YES_NO	FLAG	NO	YES	NO	PermitFuzzyMr2 = NO
PermitFuzzyMr3	Enable fuzzy control at this meter	YES_NO	FLAG	NO	YES	NO	PermitFuzzyMr3 = NO
QueueOccHigh1	High end of dynamic range for Queue Occupancy, lane 1	USHORT1P	%	0.0%	100.0%	30.0%	QueueOccHigh1 = 30.0%
QueueOccHigh2	High end of dynamic range for Queue Occupancy, lane 2	USHORT1P	%	0.0%	100.0%	30.0%	QueueOccHigh2 = 30.0%
QueueOccHigh3	High end of dynamic range for Queue Occupancy, lane 3	USHORT1P	%	0.0%	100.0%	30.0%	QueueOccHigh3 = 30.0%
QueueOccLow1	Low end of dynamic range for Queue Occupancy, lane 1	USHORT1P	%	0.0%	100.0%	12.0%	QueueOccLow1 = 12.0%
QueueOccLow2	Low end of dynamic range for Queue Occupancy, lane 2	USHORT1P	%	0.0%	100.0%	12.0%	QueueOccLow2 = 12.0%
QueueOccLow3	Low end of dynamic range for Queue Occupancy, lane 3	USHORT1P	%	0.0%	100.0%	12.0%	QueueOccLow3 = 12.0%
QueueOccWt1	Weight for Queue Occupancy Rule, Lane 1	UBYTE1	N/A	0.0	25.5	2.0	QueueOccWt1 = 2.0
QueueOccWt2	Weight for Queue Occupancy Rule, Lane 2	UBYTE1	N/A	0.0	25.5	2.0	QueueOccWt2 = 2.0
QueueOccWt3	Weight for Queue Occupancy Rule, Lane 3	UBYTE1	N/A	0.0	25.5	2.0	QueueOccWt3 = 2.0

Changes to build_rmdb.c

Build_rmdb opens and reads rmdb_input.fil, builds RMDB, creates temporary files (loop_names.lst, inc_det.eqn, btl_neck.eqn, speed_traps.lst, stn_aggr.eqn, station_names.lst, actv_anal.eqn) that are later used to build tables in global memory for TAPS. It also sorts names, loops, stations, and speeds traps and writes them to a file rtfmdbname.srt to be used for later creation of the RTDB and Five Minute Data Base (FMDB). Build_rmdb starts a long chain of events, calling function upon function. For details on how build_rmdb works, see Taylor and Meldrum, 1997.

To incorporate the Fuzzy Logic Ramp Metering Algorithm, build_rmdb must also read the fuzzy parameters and fuzzy equations from rmdb_input.fil and create a temporary file called fuzzy_meter.eqn that is subsequently used by fuzzymeter to build the fuzzy table in global memory.

The only changes made to build_rmdb.c itself are to open the temporary equation file fuzzy_meter.eqn before reading rmdb_input.fil and to close this file after reading rmdb_input.fil. However, there are several changes in functions in rmdb_sub.c that are indirectly called from build_rmdb.c.

Changes to rmdb_sub.c

Process_input_special_case is called from **get_param**. A pointer to the function **get_param** is in the read_fddb_file, which contains a function state table that tells **read_fddb** (called from build_rmdb) how to parse the input file rmdb_input.fil. **Process_input_special_case** calls functions to handle the current input line, depending on the current group index. The only change to **process_input_special_case** is to call **get_fuzzy_eqn** when the current group index is FUZZY_EQNS.

Two new functions were added to rmdb_sub.c: 1) **get_fuzzy_eqn** and 2) **get_next_fuz_line**. Note: Fuzzy parameters are not a special parameter case, so they are handled by **load_param**, which is called from **get_param**.

1) **Get_fuzzy_eqn** — Parses current line from data file and writes it to a fuzzy equation file in a fixed format. (See training manual on how to write fuzzy equations, Taylor and Meldrum, 2000.) (Note: The return values are used differently than they are for the other functions called from **process_input_special_case**. **END_LINE** is returned regardless of error or success so that **get_param** does not continue to parse the same line. If an error occurs, the message is logged by **fddb_error**, and the line is skipped by returning **END_LINE**.)

- Calculate pointer to data column
- Make sure data column is a RAMP_MTR or DATA_STN. Otherwise, write error message and return to get next line
- Get cabinet:loop name from line buffer using strtok

Note: strtok uses 1 or more skip characters as delimiters between tokens. Strtok returns the pointer to the next token in the input buffer and writes a NULL at the end of the token. Subsequent calls using NULL as the first argument continue to parse the same buffer and remember the current location

- Verify that cabinet:loop name is in proper format with **get_cab_loop_name**
- If the cabinet name does not match the current group name

Write error to **fddb_err** and return to get next line

- If string is not of fuzzy equation type containing string 'FM'
Write wrong equation type error to **fddb_err** and return to get next line
- Initialize current pointer to the beginning of a buffer that will subsequently be written to fuzzy equation file

Note: Before writing the reformatted equation is written to the fuzzy equation file, the buffer is written to a temporary buffer. This buffering technique allows writing over the equation (skipping) if an error is found.

- Write cabinet:loop name to buffer and update pointer
- Initialize number of loops written to this line to 1
- For each station location
 - Initialize the number of station/loops at this location to zero
 - **Do-while** stations are of same type (the loop executes the first time and continues to execute as long as the '&' delimiter is between station names)

Note: '&' is used to delimit between two stations of the same location type, and '|' is used to delimit stations of different location type

- If the allowable number of loops is exceeded, write error message to **fddb_error**

One loop or station is allowed for the UP and HOV_BYPASS input (see training manual). The LOCAL, QUEUE and ADV_QUEUE allow up to five loops or stations. The DOWNSTREAM input allows up to 20 loops or stations

- Get cab:loop name from input line using strtok
- If no token is found
 - Get next line from input file with **get_next_fuz_line**
 - If line_type is not a parameter, write error message to **fddb_error** and return to get next line
 - Try again to get loop detector (or station) name from input line using strtok
- Verify that cabinet:loop name is in proper format with **get_cab_loop_name**
- If the cabinet name does not match the current group name

Write error to **fddb_err** and return to get next line

- If this location is QUEUE, ADV_QUEUE, or HOV_BYPASS, get the number of samples used to calculate the input or % adjustment applied to lane
- If number of samples or % adjustment is not found

Write error to **fddb_err** and return to get next line

- If location is HOV_BYPASS
 - If % adjustment applied to lane is outside of 0-100 range

Write error to **fddb_err** and return to get next line

- If loop name is not of HOV passage type containing string “HP”

Write error to **fddb_err** and return to get next line

- If location is ADV_QUEUE
 - If loop name is of HOV passage type containing string “HP”

Write error to **fddb_err** and return to get next line

- Increment the number of loops found for this station

- If the number of loops already written to this line in buffer is 3, begin on next line because this line is full
- If the location is QUEUE, ADV_QUEUE, or HOV_BYPASS
Write the detector name and number of samples or percentage of adjustment to buffer and update buffer pointer
- Else
Write detector name to buffer and update buffer pointer
- Increment the number of loops written to this line in buffer
- Get delimiter from input line using strtok (expecting `&' or `|' to continue equation)
- If location is greater than or equal to ADV_QUEUE and delimiter is not found
End of successful equation was found. Write equation to buffer and return.
- Else if delimiter is not found
Not expecting end of equation. Write error message with **fddb_error** and return to get next line
- Else if token is `&'
Write delimiter to buffer and update pointer
- End of do-while no more stations of this type
- If location is HOV BYPASS and delimiter is `|', error because too many locations
Write error message with **fddb_error** and return to get next line
- Else If delimiter is not equal to `|', there is a missing delimiter. (The equation was expected to continue.)

Write error message with **fddb_error** and return to get next line

- Else write delimiter to buffer and update pointer
- End for each station location

2) **Get_next_fuz_line** — This new function is called from **get_fuzzy_eqn** when a fuzzy equation continues past more than one line. This function is identical to **get_next_btl_line** (located in /fddb/rmdb/rmdb_sub.c) except for the error message. Although the same function could have been used for both with slight modification, changes to bottleneck were avoided.

- Loop until line type returned by **get_next_fuz_line** is a blank, form feed, or comment
Get_next_line returns line_type of comment, curly_brace, square_bracket, or parameter. (See Taylor and Meldrum, 1997, for details). Line is stored in global memory tl->lb_ptr->line_buffer
- If find wrong line_type, write error
- Else return with parameter type line

Table 2. Summary of Modified Files for the Ramp Metering Data Base

FILE	MODIFICATION
Rmdb.h	<ol style="list-style-type: none"> 1) Defined indices for new group names FUZZYMETER_PARAMS and FUZZYMETER_EQNS. 2) Declared file pointer for FUZZY_METER.EQN. 3) Declared new elements _MeterRateLane1, _MeterRateLane2 and _MeterRateLane3 in 170_Data group of data column. 4) Declared 52 new Fuzzy_Meter_Parameters in data column. 5) Changed defined indices to enumerated constants.
Rmdb_tbl.c	<ol style="list-style-type: none"> 1) Added two new group: [Fuzzymeter_Parameters] and [Fuzzymeter_Equations] 2) Initialized minimum, maximum, default, and ep_mask for the new parameters in data column 3) Added 52 new Fuzzymeter_Parameters and 3 in 170_Data group to the fddb_name_table. 4) Added new Fuzzymeter_Parameters to the fddb_output_list
Build_rmdb.c	<ol style="list-style-type: none"> 1) Added Open/Close of fuzzy_meter.eqn file. 2) Deleted path for include files.
rmdb_sub.c	<ol style="list-style-type: none"> 1) Added get_fuzzy_eqn. 2) Added get_next_fuz_line. 3) Modified process_input_special_case to call get_fuzzy_eqn when the current group index is FUZZY_EQNS.
Tok_tbl.c	<p>Added fuzzy metering options to loop_name entry. Declare char arrays fuzziylane1, fuzziylane2, and fuzziylane3 to be "FM1", "FM2", and "FM3"</p>
Rmdb_func_prot.h	<p>Added function prototypes for get_fuzzy_eqn and get_next_fuz_line</p>

Real-Time Processes

To start up fuzzymeter with the other processes and incorporate the stand-alone utility watch_fuzzymeter, minor changes were made to the real-time processes. Table 3 describes the changes made to tms_startup.c, rt_skeleton.c, tms_realtime.h, event_common.h, tap.h, and stop_tms.com. For a further description of how the real-time processes work, see Taylor and Meldrum, 1997.

Table 3. Summary of Modified Files for the Real-Time Processes

FILE	MODIFICATION
tms_startup.c	<ol style="list-style-type: none"> 1) Delete paths for include *.h 2) Added start_tms_process for fuzzymeter 3) Associate event flags for watch_fuzzymeter 4) Added start_process for tmsuw 5) Changed to support a developmental version
rt_skeleton.c	<ol style="list-style-type: none"> 1) Deleted paths for include *.h. 2) Added run_process_wait for fuzzymeter 3) Added run_process_alt_bit for watch_fuzzymeter. 4) Associate to event flags for watch_fuzzymeter. 5) Added local flag wm_v_20_sec_tick. 6) Fixed version string to include 'V' on log_tms_event.
tms_realtime.h	<ol style="list-style-type: none"> 1) Added in event flags: RT_V_FUZZYMETETER_START and RT_V_FUZZYMETETER_DONE. Add event masks for those events: RT_M_FUZZYMETETER_START and RT_M_FUZZYMETETER_DONE. 2) Added WATCH_FUZZYMETETER Event Flag Cluster Name Descriptors 3) Added WATCH_FUZZYMETETER Event Flag Bit Assignment
event_common.h	Defined facility number for FUZZYMETETER
Tap.h	Defined action codes FM_TABLE_START and FM_SET_START used in fuzzy meter table

stop_tms.com	Added Stop Fuzzymeter
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Communications Protocol

To implement Fuzzy Metering, the changes listed in Table 4 were made to `opc_comm_sub.c`, `rmdc_comm.h`, `rmdc_comm.c`, `rmdc_comm_sub.c`, and `fddb.h`.

Changes to `opc_comm`

To tune the Fuzzy Metering Algorithm from the operator consoles running TMS, it is necessary that the new fuzzy parameters be sent to TMS along with the other tunable parameters. Within `opc_comm_sub.c`, a module called **`wc_search_param_tuning_list`** contains a list of parameters that are sent to TMS upon receiving a parameter request from a PC. The fuzzy metering parameters given in Table 1 were added to this module's list.

Changes to `rmdc_comm`

Prior to this project, the VAX and 170 software did not support the capability of implementing a central metering rate directly. The 170 was able to implement a metering rate *adjustment* from the central VAX (like the bottleneck metering rate adjustment), but because most of the logic was embedded in the 170 logic, the old design precluded the ability to directly implement a central metering rate. Prior to this project, the only way that it could be done was to set both the minimum and maximum allowable metering rates for a given ramp to equal the desired rate. This method was found to be too cumbersome for the implementation of the Fuzzy Logic Ramp Metering Algorithm, particularly when supporting multiple ramp metering algorithms simultaneously. For this reason, the software was altered both on the VAX and 170s to support the capability of directly implementing ramp-metering rates from the VAX.

We modified the communications protocol between the VAX and 170. This involved minor code changes to `rmdc_comm_sub.c`, `rmdc_comm.c`, and the 170. A new

data poll containing direct metering rates was created, called DATA_POLL_METER_RATE. The old data poll was renamed DATA_POLL_RATE_ADJ. The command bytes for these data polls were defined in rmdc_comm.h as shown in Figure 1. The new data poll is requested from rmdc_comm.c and rmdc_comm_sub.c, which builds and sends it using a new module called **build_and_queue_170_meter_rate** (Figure 1).

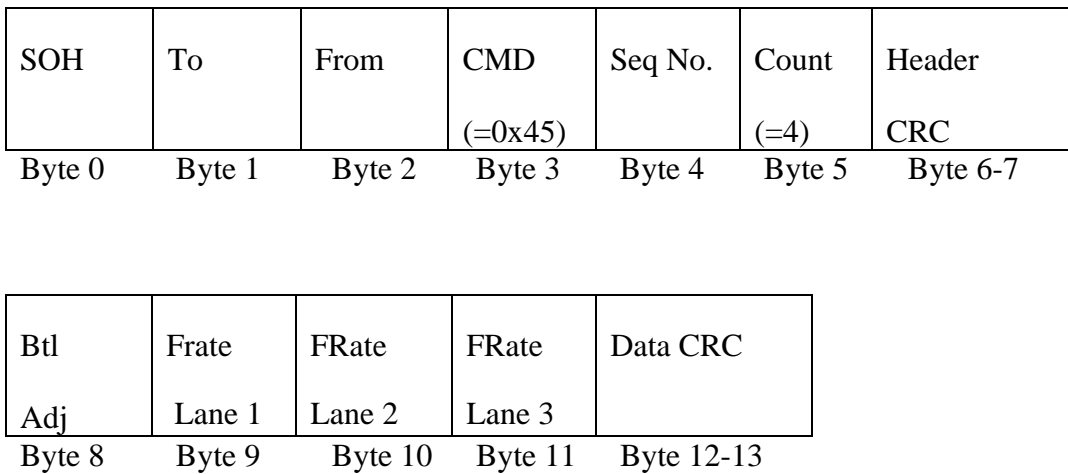


Figure 1. New Poll Format for Central Metering Rates

Table 4. Summary of Modified Files for Communications Protocol

FILE	MODIFICATION
opc_comm_sub.c	Fuzzy Parameters added to parameter list in wc_search_param_tuning_list
Rmdc_comm.h	<ol style="list-style-type: none"> 1) Renamed DATA_POLL to DATA_POLL_RATE_ADJ 2) Defined DATA_POLL_METER_RATE as 0x45
Rmdc_comm.c	<ol style="list-style-type: none"> 1) Renamed DATA_POLL to DATA_POLL_RATE_ADJ. 2) Added new case to handle data poll DATA_POLL_METER_RATE on line 1782. The new case calls process_data, which handles the DATA_POLL_METER_RATE the same as the case for DATA_POLL_RATE_ADJ. 3) Replaced call to build_and_queue_170_msg with call to build_and_queue_170_meter_rate for test case on line 2725. 4) Replaced call to build_and_queue_170_msg with call to build_and_queue_170_meter_rate for multi_port case on line 2992 5) Added if-else to send statement to send appropriate data poll. This if statement is not necessary now that all of the 170s can handle the new data poll.
Rmdc_comm_sub.c	<ol style="list-style-type: none"> 1) Renamed DATA_POLL to DATA_POLL_RATE_ADJ, line 2914. 2) Added new data poll function on build_and_queue_170_meter_rate, line 2922. 3) Replaced test menu case 'P' to build_and_queue_170_meter_rate from build_and_queue_170_msg, line 6761. 4) Added if-else to send appropriate type of data poll. This if statement is not necessary now that all of the 170s can handle the new data poll.
fddb.h	Redefined Lane Status 0x0F from LS_COMM_FAIL to LS_FUZZY.

It is possible for bottleneck and fuzzymeter to operate simultaneously on different lanes within the same cabinet (although this is not recommended). Because fuzzy metering is lane specific while bottleneck is cabinet specific, there is not a flag to indicate whether bottleneck or fuzzymeter is in effect for that cabinet. Instead, a fuzzy metering rate of 0 indicates to the 170 that fuzzy metering is disabled for that lane. If the fuzzy metering rate is disabled or cannot be calculated because of insufficient data, the bottleneck metering rate is used on that lane, unless bottleneck is also disabled. If both central algorithms are disabled, the 170 determines the metering rate, which is usually the local metering rate. Essentially, the control hierarchy is unaltered except that fuzzy metering has been added to the top of the ramp metering decision tree. In general, inexplicit override of one controller over another is undesirable but was difficult to avoid in this case because fuzzymeter is lane specific while bottleneck is cabinet specific. For further details regarding the control hierarchy between the ramp metering algorithms, see the training manual (Taylor and Meldrum, 2000).

Fuzzymeter is similar to bottleneck in that both algorithms disable the central metering rate or rate adjustment before writing over it. Every time bottleneck is called, it writes -128 to the metering rate adjustment for all cabinets, which has the effect of disabling the Bottleneck adjustment if -128 is sent to the 170. Then bottleneck writes over the adjustments for which OperPermitBtl is enabled. Likewise, Fuzzymeter initially writes 0 into MeterRateLane1, MeterRateLane2, and MeterRateLane3, which signifies to the 170 that the metering rates are disabled. If PermitFuzzy1, PermitFuzzy2, or PermitFuzzy3 is enabled, fuzzy metering calculates a metering rate for the specified lanes and writes over the disabled metering rates.

In the future, it may be desirable to add a third central metering algorithm and have the capability to choose between them. It would not be difficult to add this capability. Additional parameters will need to be added to data columns within RMDB, including flags to indicate which algorithm to use in each lane and storage space for the metering rates generated by each central algorithm. If logic were to be used to choose a metering rate, this new main would be treated as an additional TAP. Because each TAP is completed before the next begins, logic to choose metering rates could use the results from fuzzymeter, bottleneck, and any additional algorithms. (However, because the fuzzy logic controller already uses system-wide information to arrive a metering rate, we expect that performance would degrade with a piece-meal control approach.)

Changes to fddb.h

The lane status is among the data returned from the 170 to the VAX. The interpretation of the lane status has been redefined as shown in Table 5. The value of the lane status indicates the mode of metering last implemented by the 170.

Table 5. Lane Status

Value	Group Meter Status	Single Meter Status	Condition
0x00	OFF	Meter Off	Meter Off
0x01	(L)	(L)	Local rate used
0x02	(L)Q	(L) Q Adjust	Local w/ Queue Adjustment
0x03	(L)AQ	(L) AQ Adjust	Local w/ Advance Q Adjustment
0x04	(B)	(B)	Bottleneck rate used
0x05	(B)Q	(B)Q Adjust	Bottleneck w/ Queue Adjustment
0x06	(B)AQ	(B) AQ Adjust	Bottleneck w/ Advance Q Adjustment
0x07	(P)	(P)	Prediction rate used
0x08	(P)Q	(P) Q Adjust	Prediction w/ Queue Adjustment
0x09	(P)AQ	(P) AQ Adjust	Prediction w/ Advance Q Adjustment
0x0A	(T)	(T)	TOD rate used
0x0B	(T)A	(T) Q Adjust	TOD w/ Queue Adjustment
0x0C	(T)AQ	(T) AQ Adjust	TOD w/ Advance Q Adjustment
0x0D	-P-	Police Mode	Police Mode – Steady Green
0x0E	E	D/F	Comm is Failed or Disabled
0x0F	FUZY	Fuzzy Control	Fuzzy Meter Control

170

To correctly interpret the new data poll containing direct metering rates, the 170 logic was modified. Because fuzzymeter directly implements a rate without further adjustments, the new logic must bypass the local logic within the 170 when this occurs. This design allows the existing logic to remain in place and operate as before, unless a nonzero (enabled) fuzzy metering rate is provided. The new logic functions in this way:

For each lane

- If fuzzy metering rate > 0 (it is not disabled)
 Implement fuzzy meter rate
- Else
 Proceed with logic for other ramp metering algorithms

The 170 interprets the fuzzy metering rate as an unsigned byte ranging between 0 and 255, corresponding to metering rates between 0 and 25.5 VPM. (The bottleneck adjustment ranges between -12.8 and 12.7 VPM.)

Note that any central ramp-metering algorithm which needs to directly implement a metering rate can use this same mechanism by putting the desired metering rates in MeterRate1, MeterRate2, and MeterRate3 of the RMDB. Rmdc_comm will send the direct rates through the new data poll, and the 170 will implement them. The use of the new data poll and new 170 logic is not limited to use by fuzzymeter. Currently, Fuzzy Metering is the only algorithm that implements rates directly.

Utilities

Minor modifications were made to the utilities listed in Table 6.

Table 6. Summary of Modified Files for Utilities

FILE	MODIFICATION
Get_20_sec_data.c	Defined GET_20_LOG in order to create text files. Ifdef's have been added so that *.dat files are no longer created unless GET_20_DAT is defined.
Watch_actv_anal.c	Moved mvwrtstr and mvwrtstr_attrib to watch_sub.c
Watch_bottleneck.c	Moved mvwrtstr and mvwrtstr_attrib to watch_sub.c
Watch_fmdb.c	Moved mvwrtstr and mvwrtstr_attrib to watch_sub.c
Watch_rmdb.c	Moved mvwrtstr and mvwrtstr_attrib to watch_sub.c
Wfmdb.c	Moved mvwrtstr and mvwrtstr_attrib to watch_sub.c
Wrtdb.c	Moved mvwrtstr and mvwrtstr_attrib to watch_sub.c
Tms_lib_func_prot.h	Added mvwrtstr , mvwrtstr_vertical , mvwrtstr_attrib , mvwrtstr_underline

NEW CODE

To implement the Fuzzy Logic Ramp Metering Algorithm, the new files in Table 7 were created. These files reside in the directory `tms_code/rt_skeleton/fuzzymeter`. Overall, approximately 8000 lines of code were added to the TMS VAX software.

Table 7. Summary of New Files for Fuzzy Metering

FILE	FUNCTION
Fuzzymeter.c	Main process called every 20 seconds from rt_skeleton for calculating rates. Calls build_fuzzymeter_table and calc_fuzzymeter .
Watch_fuzzymeter.c	Stand alone process, updated every 20 seconds when called by rt_skeleton. Calls to build_watch_fuzzymeter_table and calc_watch_fuzzymeter .
Fuzzymeter_sub.c	Contains modules called by watch_fuzzymeter and fuzzymeter: build_fuzzymeter_table, build_watch_fuzzymeter_table, calc_fuzzymeter, calc_watch_fuzzymeter, calc_fuzzy_rate, calc_watch_fuzzy_rate, fuzzify, rules, watch_rules, and defuzzify.

Fuzzy.h	Contains definitions, structures, function prototypes, and compile options for fuzzymeter and watch_fuzzymeter.
Watch_sub.c	mvwrtstr — Move Cursor and Write String mvwrtstr_attrib — Move Cursor and Write String w/ Attributes mvwrtstr_vertical — Move Cursor and Write String Vertically mvwrtstr_underline — Move Cursor and Write Underline
Edit_20_sec.c	A stand-alone utility that automatically rewrites the input file used by get_20_sec_data and starts the 20-second data collector at the desired time. Allows automatic weekday collection of specified data for the morning and afternoon metering periods. This process is not required to run fuzzymeter, nor is it required to run start_20_sec (which starts get_20_sec_data). See Performance Evaluation Software for discussion.

Fuzzymeter.c

Fuzzymeter starts up the main, builds the fuzzymeter analysis table, and then waits for an event flag from the real time skeleton to calculate metering rates. Fuzzymeter is integrated as a TAP and is designed in a parallel manner to the other TAPS.

- **General_process_startup**
 - **Connect_to_mailbox**
 - **Write_to_crash_log**
 - Associate to event flag cluster
 - Clear all event flags
- **Log_tms_event**
 - **Log_tms_common**
 - **Write_to_crash_log**
 - Get time
 - Compose message
 - **Write_to_mailbox_nowait**
- **Map_to_RTDB**
 - **Map_to_global_section**
 - **Init_rtdb_tl**
- **Map_to_RMDB**
 - **Map_to_global_section**
 - **Init_rmdb_tl**

- **Build_fuzzymeter_table** (see fuzzymeter_sub.c)
- **While** SHUTDOWN_TMS event flag is clear
 - Wait for fuzzymeter start event flag with SYS\$WAITFR
This flag gets set in rt_skeleton by SYS\$SETEF
 - Clear fuzzymeter start flag with SYS\$CLREF
 - **calc_fuzzymeter** (see fuzzymeter_sub.c)
 - Set fuzzymeter done flag with SYS\$SETEF
 - Test shutdown flag with SYS\$READEF
cond_code of SS\$_WASCLR means do not shutdown
cond_code of SS\$_WASSET means shutdown

Watch_fuzzymeter.c

Watch_fuzzymeter is a stand-alone utility. Upon start up, watch_fuzzymeter builds the watch_fuzzymeter analysis table. The user chooses which metered lane to observe. Upon receiving an event flag from rt_skeleton, watch_fuzzymeter writes the controller crisp inputs, fuzzified inputs, and rule outcomes, rule weights, and metering rates are written to the screen. Watch_fuzzymeter is integrated as a utility program and is designed in a manner parallel to the other utility programs.

- **Map_to_RTDB**
 - **Map_to_global_section**
 - **Init_rtdb_tl**
- **Map_to_RMDB**
 - **Map_to_global_section**

- **Init_rmdb_tl**
- **Get_iochan** – usually keyboard
- **Get_term_char** —get I/O channel number for TTY port
- **Set_port_partial** – TTY driver handles flow control
- **Build_watch_fuzzymeter_table** (see fuzzymeter_sub.c)
- If no fuzzy equation sets were returned by **build_watch_fuzzymeter_table**
 - Print error message
 - Set error_flag to YES
- Else
 - Set error_flag to NO
- **While** error_flag is NO
 - Print Banner
 - Print User Options
 - Get a character from user input
 - Convert character to upper case
 - If user did not choose watch fuzzymeter
Break from while loop
 - Else
Print user input
- **Select_cabinet** – writes cabinet list to screen and receives user input
- If user chose a cabinet numbered < 0
 - Print error message

- Continue while loop
- **get_tty_bit** – Set up TTY event flag bit and return bit number
- **one_bit_mask** – create mask for bit
- SY\$ASCEFC – Associate to watch_fuzzymeter’s event flag cluster
- If condition code returned by SY\$ASCEFC is not normal
 - Print error message
 - Continue while loop
- **Two_bit_mask** – create mask for two bits
- Create a mask to watch for either of two events: the start of watch fuzzymeter or a keyboard interrupt
- SM\$CREATE_PASTEBOARD – Establish terminal screen as pasteboard
- SM\$CHANGE_PBD_CHARACTERISTICS – Change pasteboard size to 132 columns and 24 rows.
- SM\$CREATE_VIRTUAL_DISPLAY – Establish entire screen as a virtual display
- SM\$CREATE_VIRTUAL_DISPLAY – Establish a virtual display for the cabinet name, date and time window
- SM\$CREATE_VIRTUAL_DISPLAY – Establish a virtual display for the prompt message window
- SM\$CREATE_VIRTUAL_DISPLAY – Establish a virtual display for the diagnostic message window
- SM\$PASTE_VIRTUAL_DISPLAY – Paste entire screen as a virtual display

- SMG\$PASTE_VIRTUAL_DISPLAY – Paste a virtual display for the prompt message window
- SMG\$PASTE_VIRTUAL_DISPLAY – Paste a virtual display for the cabinet name, date and time window
- SMG\$PASTE_VIRTUAL_DISPLAY – Paste a virtual display for the diagnostic message window
- SMG\$DRAW_LINE – Draw horizontal lines on the I/O window
- SMG\$DRAW_LINE – Draw vertical lines on the I/O window
- SMG\$DRAW_LINE – Draw horizontal lines on the rules window
- SMG\$DRAW_LINE – Draw vertical lines on the rules window
- Get cabinet name from indexed cabinet list
- **Find_fddb_cl_name** – retrieve index to specified cabinet within RMDB
- Calculate pointer to cabinet column in RMDB
- Retrieve cabinet's roadway type from RMDB
- Retrieve cabinet's milepost from RMDB
- Retrieve cabinet's location name from RMDB
- Put cabinet name, roadway, milepost, and location into a string
- Write string to cabinet window
- Write prompt message to prompt window
- Write headers for I/O window
- Write headers to rule window
- **Queued_get_1_char** – queue up a read request for a character from the keyboard

- SYSS\$CLREF – Clear the TTY interrupt bit
- SYSS\$WFLOR – Wait for start of watch_fuzzymeter
- SYSS\$READEF – Read condition code of start condition
- **While** there is no keyboard interrupt and no errors occur
 - Calculate the alternative bit of whichever of two bits that last started watch_fuzzymeter (as set by rt_skeleton), and perform bitwise OR of that bit with the keyboard interrupt to watch for either of these two events
 - Calculate the pointer to the current data column of the RTDB
 - Get time stamp of the RTDB
 - Get communication status of cabinet
 - Write communication status and time into string
 - Print string to cabinet window
 - **Calc_watch_fuzzymeter** – calculate a metering rate and return data and diagnostic flag (see fuzzymeter_sub.c)
 - If diagnostic flag is YES (**calc_watch_fuzzymeter** could not successfully calculate a fuzzy metering rate)
 - SMG\$ERASE_DISPLAY — Erase old I/O data
 - SMG\$ERASE_DISPLAY — Erase old rule data
 - Convert the rule weights from floats to integers to use them as data validity flags. (The rule weights were set to zero by **calc_watch_fuzzymeter** if their input data was bad)

- If the local occupancy input has good data
 - Write the local occupancy and local speed data to the I/O window
 - If the downstream input has good data, write the downstream occupancy and downstream speed to the I/O window
 - If the queue input has good data, write the queue data to the I/O window
 - If the advance queue input has good data, write the advance queue data to the I/O window
 - Write the HOV data to the I/O window. (A zero HOV bypass volume may mean that there was zero passage or that the data were bad.)
- Write diagnostic message to the diagnostic window
- Else (diagnostic flag was NO — **calc_watch_fuzzymeter** successfully calculated a metering rate)
 - SMG\$ERASE_DISPLAY – erase diagnostic window
 - Write data to I/O window
 - Scroll old metering rate data on I/O window
 - Write new metering rate data to I/O window
 - Write rule weights to rule window
 - Write rule outcomes to rule window
 - Move cursor to the end of prompt message on prompt window
- Wait for start of watch_fuzzymeter

- SYS\$WFLOR – Wait for start of watch_fuzzymeter
- SYS\$READEF – Read condition code of start condition

- If interrupt bit was set
 - Clear the TTY interrupt bit
 - Associate to the TTY Reservation EFC
 - Clear the TTY reservation bit
 - Clear any outstanding TTY input
 - SMG\$DELETE_PASTEBOARD – unpaste all virtual displays and clear screen

- Cancel any outstanding input from the keyboard
- SMG\$DELETE_PASTEBOARD – unpaste all virtual displays and clear screen
- Restore the saved TTY characteristics

Fuzzymeter_sub.c

Fuzzymeter_sub.c contains modules which are called from the main processes fuzzymeter and watch_fuzzymeter. Watch_fuzzymeter displays fuzzymeter's input, internal calculations, and output for a specified metered lane. Ideally, these processes would share identical modules to ensure that they use the same data and calculations. However, this module sharing was not entirely feasible for a couple of reasons. Watch_fuzzymeter does its calculation during a different time frame of the real-time data cycle, so it must use indices different than those of fuzzymeter for the recently scrolled RTDB. We did not want to clutter up a global database by storing all of the internal

calculations for all ramp meters, nor did we want to slow processing time of the TAPS. Instead, `watch_fuzzymeter` stores an index of pointers for each metered lane. When users specify the metered lane that they want to examine, internal data are stored for only that metered lane. In general, `watch_fuzzymeter`'s modules need to store additional information in addition to that of `fuzzymeter`, but otherwise their modules are identical. Each row of Table 8 list the parallel modules called from `fuzzymeter` and `watch_fuzzymeter`, along with a brief overview. If you make a change to one of these `fuzzymeter` modules, be sure that you examine the parallel `watch_fuzzymeter` module to see if it needs the change as well.

Table 8. Parallel modules called from Fuzzymeter and Watch_fuzzymeter

Fuzzymeter Modules	Watch_fuzzymeter Modules	Overview
Build_fuzzymeter_table	Build_watch_fuzzymeter_table	Builds of table of pointers to the RMDB and RTDB data needed to calculate the metering rates for each lane
Calc_fuzzymeter — Calls calc_fuzzy_rate	Calc_watch_fuzzymeter — Calls calc_watch_fuzzy_rate	Obtains the inputs to the controller
Calc_fuzzy_rate — Calls fuzzify , rules , and defuzzify	Calc_watch_fuzzy_rate — Calls fuzzify , watch_rules , and defuzzify	Calculates the metering rate
Fuzzify	Fuzzify	Converts each crisp input into a set of fuzzy classes
Rules	Watch_rules	Evaluates rule base
Defuzzify	Defuzzify	Converts a set of fuzzy metering rates to a single

		numerical metering rate
--	--	-------------------------

Build_fuzzymeter_table — Parses the fuzzymeter equation file (which was created by build_rmdb and must adhere to the format specified in the training manual, Taylor and Meldrum, 2000) searches for the cabinet name in RMDB and station names in RTDB, and writes the action codes and data pointers to fuzzymeter table. (See Table 9.)

- Initialize memory allocation for fuzzymeter table
- Write header to table: start table label, number of sets, table size, date/time
- Open fuzzymeter equation file
- Initialize counters and flags

- **While** not EOF, read line of fuzzy_meter.eqn (equation file)
 - Get cabinet name at start of equation
 - Initialize location to LOCAL
 - Save pointer to beginning of set
 - Initialize error flag to no error
 - **Find_fddb_cl_name** — Search for cabinet name in Field Device Data Base (FDDB) and return index
 - Extract metered lane number from the cabinet:loop name
 - If cabinet name is not in RMDB, write error message and set error flag
 - If "FM" is not given after cabinet name to be fuzzy metered, write error message and set error flag
 - If an error occurred, send error message and search for beginning of next equation

- If more memory is needed to write next set, allocate additional memory
- Write set header to table: start set code, lane number, space for number of bytes in set, pointer to cabinet in RMDB (for metered lane to be fuzzy metered)
- Get token from eqn_file

- **While** token is a delimiter (not end of equation)
 - If token is `|`, increment location
 - Get next token. Expecting a station:loop name
 - If a token is not returned
 - **Build_tap_error** — station:loop name not found
 - Set error flag
 - Break out of while-loop to skip equation. (Error handling at end of while-loop resets pointer to the beginning of set and looks for next equation.)
 - If location is QUEUE, ADV_QUEUE, or HOV_BYPASS
 - Parse token with strtok to get the station:loop name
 - If station:loop name is not found, set error flag and break out of while-loop to skip this equation
 - Parse same token with strtok to get a number token which represents either the number of samples to calculate input or the percentage of HOV bypass volume adjustment applied to this lane
 - If number token is not found, set error flag and break out of while-loop to skip this equation
 - Convert number of samples from ASCII to integer

- If number of samples is less than 128, convert it to an unsigned char (1 byte)
- Else number token is OK
 - **Build_tap_error** — number of samples is too large
 - Set error flag
 - Break out of while-loop to skip this equation
- Else
 - Store station:loop name
- If location is HOV_BYPASS
 - If loop name is not of type “HP”
 - Set error flag
 - Break out of while-loop to skip this equation
- Write location code to table
- **Search_rtdb_name_table** — search for index to loop in RTDB
- If loop index is not found
 - **Build_tap_error** – “Stn/Loop name is not in RTDB”
 - Set error flag
 - Break out of while-loop to skip this equation
- Else station/loop name is good
 - Obtain offset in table for stn_loop in RTDB based on index
 - Write offset to table

- If location is QUEUE, ADV_QUEUE, or HOV_BYPASS, write number of samples or percentage of HOV bypass to table
- Get next token — expecting a delimiter or cabinet
- If next token is NULL (OK if EOF)
 - **build_tap_error** — Null result when parsing fuzzy equation set error flag
 - Set error flag
 - Break out of while-loop to skip this equation
- End of while-loop that reads equation
- If location is less than ADV_QUEUE
 - Point to set start to skip this equation because it does not have enough station locations. (Fscanf has already grabbed the next token.)
- Else if no errors occurred (the equation is good)
 - Increment the number of sets in the table
 - Calculate the number of bytes in the set
 - Write the number of bytes in set to table
- Else an error occurred during parsing (NULL fscanf result)
 - Point to set start to skip this equation
 - Get token to search for next equation
- End of while-loop to read file of equations
- Close fuzzy equation file
- Write number of sets and table size into table header

- Write table end label, check sum (calculate number bytes in table)
- Trim table size
- Return base address of table

Table 9. Description of the Fuzzy Table's Layout in Memory

LABELS	ITEM	# BYTES	DESCRIPTION
----- (begin table)			
table_base->	code	1	FM_TABLE_START
	ushort	2	number of sets
	ulong	4	table size
	date_time	8	struct system_time
----- (end of table header)			
----- (beginning of sets)			
set_start	code	1	FM_SET_START
	byte	1	lane_no -- which ramp lane to meter (1, 2, or 3)
	byte	1	# of bytes in set
	ulong	4	col_ptr to cabinet in RMDB (to get fuzzy parameters)
----- (end of a set header)			
----- (begin local stations)			
	byte	1	LOCAL -- adjacent mainline station type
	ushort	2	rtdb_offset to LOCAL station in RTDB
----- (repeat for each local input)			
	byte	1	DOWN -- downstream station type
	ushort	2	rtdb_offset to downstream station in RTDB
----- (repeat for each downstream input)			
	byte	1	UP -- upstream station type
	ushort	2	rtdb_offset to upstream station in RTDB
----- (end of upstream input)			
	byte	1	QUEUE -- ramp queue station type
	ushort	2	rtdb_offset to queue loop in RTDB
	byte	1	# of samples to calculate queue_occ
----- (repeat for each queue input)			
	byte	1	ADV_QUEUE -- station type
	ushort	2	rtdb_offset to advance queue loop in RTDB
	byte	1	# of samples to calculate adv_queue_occ
----- (repeat for each advance queue input)			
	byte	1	HOV_BYPASS -- this input is optional
	ushort	2	rtdb_offset to bypass loop in RTDB
	byte	1	percentage of HOV bypass volume adjustment to apply
----- (end of HOV input)			
----- (end of a set)			
----- (begin next set)			
Repeat for each set (every metered lane of every cabinet with fuzzy metering)			
----- (end of all sets)			
----- (label end of table)			
	code	1	TABLE_END
	short	2	check sum -- # of bytes in table
----- (end of table)			

Build_watch_fuzzymeter_table — This module is identical to **build_fuzzymeter_table**, except that it stores an array of structures containing pointers to the beginning of each set for every metered lane and then returns the number of sets. Subsequently, the set number that the watch_fuzzymeter user chooses is the index to the array of structures of pointers to access the specified data set.

- Initialize memory allocation for cabinet list
- Initialize memory allocation for fuzzymeter table
- Write header to table: start table label, number of sets, table size, date/time
- Open fuzzymeter equation file
- Initialize counters and flags

- **While** not EOF, read line of FUZZY_METER.EQN (equation file)
 - Get cabinet name at start of equation
 - Initialize location to LOCAL
 - Save pointer to beginning of set
 - Initialize error flag to no error
 - **Find_fddb_cl_name** — Search for cabinet name in Field Device Data Base (FDDDB) and return index
 - Extract metered lane number from the cabinet:loop name
 - If cabinet name is not in RMDB, write error message and set error flag
 - If "FM" is not given after cabinet name to fuzzy meter, write error message and set error flag

- If an error occurred, send error message and search for beginning of next equation
- If more memory is needed to write next set, allocate additional memory
- Write set header to table: start set code, lane number, space for number of bytes in set, pointer to cabinet in RMDB (for fuzzy parameters)
- Get token from eqn_file

- **While** token is a delimiter (not end of equation)
 - If token is `|`, increment location
 - Get next token. Expecting a station:loop name
 - If a token not returned
 - **build_tap_error** — station:loop name not found
 - Set error flag
 - Break out of while-loop to skip equation. (Error handling at end of while loop resets pointer to the beginning of set and looks for next equation)
 - If location is QUEUE, ADV_QUEUE, or HOV_BYPASS
 - Parse token with strtok to get the station:loop name
 - If station:loop name is not found, set error flag and break out of while-loop to skip this equation
 - Parse same token with strtok to get a number token which represents either the number of samples to calculate input or the percentage of HOV bypass volume adjustment applied to this lane
 - If number token is not found, set error flag and break out of while-loop to skip this equation

- Convert number of samples from ASCII to integer
- If number of samples is less than 128, convert it to an unsigned char (1 byte)
- Else number token is OK
 - **Build_tap_error** — number of samples is too large
 - Set error flag
 - Break out of while-loop to skip this equation
- Else
 - Store station:loop name
- If location is HOV_BYPASS
 - If loop name is not of type “HP”
 - Set error flag
 - Break out of while-loop to skip this equation
- Write location code to table
- **Search_rtdb_name_table** — search for index to loop in RTDB
- If loop index is not found
 - **Build_tap_error** – “Stn/Loop name is not in RTDB”
 - Set error flag
 - Break out of while-loop to skip this equation
- Else station/loop name is good
 - Obtain offset in table for stn_loop in RTDB based on index
 - Write offset to table

- If location is QUEUE, ADV_QUEUE, or HOV_BYPASS, write number of samples or percentage of HOV bypass to table
- Get next token — expecting a delimiter or cabinet
- If next token is NULL (OK if EOF)
 - **Build_tap_error** — Null result when parsing fuzzy equation set error flag
 - Set error flag
 - Break out of while-loop to skip this equation
- End of while-loop that reads equation

- If location is less than ADV_QUEUE
 - Point to set start to skip this equation because it does not have enough station locations. (Fscanf has already grabbed the next token.)
- Else if no errors occurred (the equation is good)
 - Increment the number of sets in the table
 - Calculate the number of bytes in the set
 - Write the number of bytes in set to table
 - If necessary, get additional memory for the cabinet list
 - Write the pointer of the set beginning to the cabinet list
- Else an error occurred during parsing (NULL fscanf result)
 - Point to set start to skip this equation
 - Get token to search for next equation
- End of while-loop to read file of equations

- Close fuzzy equation file
- Write number of sets and table size into table header
- Write table end label, check sum (calculate number bytes in table)
- Trim table size
- Return base address of table

Calc_fuzzymeter — When called from the main every 20 seconds, **calc_fuzzymeter** processes the fuzzymeter table one line at a time (Table 9), obtaining fuzzy parameters from RMDB and getting data from RTDB. After parsing a set (for a metered ramp), it calls **calc_fuzzy_rate**, which returns a metering rate. **Calc_fuzzymeter** writes it to the RMDB. (Rmdc_comm subsequently sends the new data poll with these direct metering rates and the 170 bypasses local logic to directly implement them.)

- For all data columns in RMDB
 - Skip if data column for min, max, default or prot mask
 - Initialize the fuzzy metering rate to 0 for lanes 1, 2, and 3. The 170 interprets 0 to mean that fuzzy metering is disabled for that lane.
- Initialize pointer to beginning of fuzzy meter table
- Skip past table header
- **While** not end of table
 - Save pointer to beginning of current set in table
 - Get metered lane number from table
 - Get bytes in set from table
 - Get station:loop offset into RTDB
 - Get pointer to data column in RMDB
 - Use column pointer to get index to current cabinet

- Set permission flag equal to PermitFuzzyMr parameter from RMDB. If lane number is not equal to 1, 2, or 3, log error and set permission flag to NO.
- If Permit Fuzzy Metering parameter is disabled,
 - Skip this set and jump pointer to the next set in table
 - Get action code that starts new set
 - Continue to beginning of while-loop
- Get fuzzy parameter high and low range limits for local occupancy, local speed, downstream occupancy, downstream speed, and upstream occupancy inputs.
- Get fuzzy parameter rule weights
- Get range limits for queue occupancy, advanced queue occupancy, and metering rate. These names are lane specific, so only get the parameters for the current lane.
- Initialize the centroid and base width fuzzification parameters to their default values that are provided with the globals at the beginning of fuzzymeter_sub.c. For the inputs that use only one input class (these are DOWN_OCC, DOWN_SPEED, QUEUE_OCC, and ADV_QUEUE_OCC), the base width of the utilized class is set to 1 so that the class will encompass the entire dynamic range. The other inputs are ignored by the controller for that input. If you want to modify the *relative* width of the classes, do so by modifying the class base width here. If you want to modify the *relative* positioning of the classes, do so by modifying the class centroids here. However, it is not expected that this will be necessary for Seattle, as adjusting the Low and High parameters is sufficient for solving nearly all problems regarding the dynamic range of the classes.

- Get next action code
- Initialize data usable flag to YES
- Initialize bypass volume to 0
- **While** fetching and processing data from RTDB station:loops
 (Note: Fuzzymeter does not initialize any data in the RTDB. It only fetches and uses the data from the RTDB and RMDB. **Calc_fuzzymeter** prepares these inputs to the controller.)
 - Initialize number of good stn/loops for this station type to zero
 - Initialize data usability flag to yes
 - Initialize number of good station:loops for this data type to zero
 - Initialize sum of volumes for this station type to zero
 - Initialize sum of scan count for this station type to zero
 - If action code is HOV_BYPASS
 Number of samples used to calculate input is 6
 - Else
 Number of samples used to calculate input is 3

- **Do-While** same station type (action codes are the same)— loop is executed at least once. For each time this loop is executed, one input to the fuzzy controller is calculated. (See rules for writing fuzzy equations in training manual for details)
 - Get station:loop offset into RTDB from table
 - If action code is QUEUE or ADV_QUEUE
 - Get number of samples used to calculate input
 - If action code is HOV_BYPASS
 - Get percentage of HOV adjustment to lane
 - For each sample needed to calculate input data
 - Calculate pointer to RTDB cabinet from station:loop offset
 - **Unpack_rtdb_loop_stn data**
 - If data are good – this occurs when the number of loops is greater than 1 (this means that it's a station, not a loop) and the flag not equal to 0 (the station data are usable) OR if the number of loops is 1 (loop data rather than station) and the flag is 1 (the loop data are good). Note: These data have already been interpolated if it is necessary and possible.
 - If action code is not DOWN
 - Increment number of good stations used to calculate this input
 - Increment number of total loops (over all stations) to calculate this input
 - Sum scan count

- Sum volume to later calculate speed
- Else action code is DOWN. (DOWN is handled differently than the other locations because it uses the maximum occupancy and associated speed rather than averaging all inputs)
 - If this occupancy is the maximum of the downstream occupancy inputs or if no other good data were found
 - Set number of good stations to calculate this input to 1
 - Set number of total loops for all stations at this location to be the number of loops returned by **unpack_rtdb_loop_stn**
 - Set sum of scan count to the scan count returned by **unpack_rtdb_loop_stn**
 - Set sum of volume to the volume count returned by **unpack_rtdb_loop_stn**
- Set old action code to equal current action code
- Get next action code
- End of do-while loop to process stations of same type
- If more than one station/loop is good, calculate controller inputs
 - Calculate average occupancy using scan count and total number of good loops
 - If location code < QUEUE (meaning that it is a mainline input)

Calculate average speed for that location using average volume and occupancy

- Switch based on old action code (detector location)
 - In LOCAL or DOWN case, enter the calculated occupancy and speed in controller input array
 - In UP case,
 - Enter the calculated occupancy into controller input array for upstream input
 - If there were no usable local data
 - Enter the upstream occupancy as the local occupancy
 - Enter the upstream speed as the local speed
 - Set data usable flag to YES
 - In QUEUE or ADV_QUEUE case, enter the calculated occupancy in the controller input array
 - In HOV_BYPASS case, convert from vehicles summed over all samples to vehicles/minute
- Else (data for this location are insufficient to calculate inputs) — Check to see if the lack of data at this location makes the rule base incomplete. If the rule base is incomplete, set the data_usable flag to NO so that local metering will be used instead.
 - Switch based on old action code (detector location)
 - In LOCAL case,

Set data usable to NO_LOCAL. (A complete rule base requires this input! Do not change this logic because the output of the fuzzy logic controller may not be undefined otherwise. The NO_LOCAL state differs from the NO state in that there is still the possibility that the upstream input will be a good substitute for the local input. In this event, the data usable state would be returned to YES.)

- In DOWN case,
Set the rule weights to zero for the rules that use downstream inputs.
(The rule base does not require this input for completeness.)
- In UP case,
Set the rule weights to zero for the rules that use this input. (By default, this input is not used for upstream rules, but only as a substitute for the local data in the event they are bad.)
- In QUEUE case,
 - Increase the advance queue rule weight by the queue rule weight to compensate for the bad queue data
 - Set the queue rule weight to zero
- In ADV_QUEUE case,
 - If the queue weight is zero (meaning that there are no usable ramp inputs), set the data usable flag to NO. (The fuzzy controller requires this input so that the resulting fuzzy metering rate is not too restrictive.)

- Else (the queue input was OK), set the advance queue rule weight to zero
 - In HOV_BYPASS case,
 - Set the HOV bypass volume to zero. (With this, no HOV bypass adjustment will occur, which is not a problem.)
- End of while-loop to process a set (an equation for 1 metered lane)
- If data are usable to calculate the metering rate at this ramp (sufficient data set contains a local input and at least one ramp queue input)
 - **Calc_fuzzy_rate** given the real-time data, fuzzification parameters, and rule weights
 - Do HOV bypass adjustment — subtract HOV bypass volume times the percentage of HOV adjustment for that lane from the metering rate
 - If adjusted metering is smaller than fuzzy minimum metering rate,
 - Set it to the fuzzy minimum metering rate
 - If the metering rate is greater than 25.5, it won't fit into 1 byte,
 - Write error message with **log_tms_event** and disable fuzzy metering rate to 0
 - Convert the metering rate from a float to an unsigned character byte
 - Write the metering rate for that lane to `_MeterRateLane1`, `_MeterRateLane2`, or `_MeterRateLane3` in the RMDB
- Else if data are not usable to calculate the metering rate at this ramp
 - Write error message with **log_tms_event**
- End of while-loop to process table

calc_watch_fuzzymeter — This module is identical to **calc_fuzzymeter** computationally, but differs in functionality. It returns a diagnostic flag indicating whether or not it was possible to calculate a metering rate. It returns a pointer to the fuzzymeter table and a diagnostic message. In global memory, it stores the controller inputs from the RTDB. Because the RTDB is scrolled after the TAPS (of which **fuzzymeter** is one), the indexing to access the RTDB for **calc_watch_fuzzymeter** varies from that of **calc_fuzzymeter**. Instead of processing all sets within the fuzzy meter table, it only processes one designated set. Instead of implementing the calculated metering rates, it stores them in global memory for **watch_fuzzymeter** to access. Instead of calling **calc_fuzzy_rate**, it calls **calc_watch_fuzzy_rate**.

- Initialize diagnostic flag to NO. (This flag indicates whether a rate could successfully be calculated.)
- Initialize pointer to beginning of set to be observed
- Get metered lane number from table
- Get bytes in set from table
- Get station:loop offset into RTDB
- Get pointer to data column in RMDB
- Use column pointer to get index to current cabinet
- Set permission flag equal to PermitFuzzyMr parameter from RMDB. If lane number is not equal to 1, 2, or 3, set permission flag to NO.
- If Permit Fuzzy Metering parameter is disabled,

- Set diagnostic flag to YES
- Put diagnostic message into diagnostic message string
- Get fuzzy parameter high and low range limits for local occupancy, local speed, downstream occupancy, downstream speed, and upstream occupancy inputs.
- Get fuzzy parameter rule weights
- Get range limits for queue occupancy, advanced queue occupancy, and metering rate. These names are lane specific; so only get the parameters for the current lane.
- Initialize the centroid and base width fuzzification parameters to their default values, which are provided with the globals at the beginning of fuzzymeter_sub.c. For the inputs that only use one input class (these are DOWN_OCC, DOWN_SPEED, QUEUE_OCC, and ADV_QUEUE_OCC), the base width of the utilized class is set to 1 so that the class will encompass the entire dynamic range. The other inputs are ignored by the controller for that input. If you want to modify the *relative* width of the classes, do so by modifying the class base width here. If you want to modify the *relative* positioning of the classes, you can do so by modifying the class centroids here. However, it is not expected that this will be necessary for Seattle, as adjusting the input or output's Low and High parameter is sufficient for solving nearly all problems regarding the dynamic range of the classes.
- Get next action code
- Initialize data usable flag to YES
- Initialize bypass volume to 0

- **While** fetching and processing data from RTDB station: loops

(Note: Watch_fuzzymeter does not initialize any data in the RTDB. It only fetches and uses the data from the RTDB and RMDB.

Calc_watch_fuzzymeter prepares these inputs to the controller.)

- Initialize number of good stn/loops for this station type to zero
- Initialize data usability flag to YES
- Initialize number of good station:loops for this data type to zero
- Initialize sum of volumes for this station type to zero
- Initialize sum of scan count for this station type to zero
- If action code is HOV_BYPASS
number of samples used to calculate input is 6
- Else
number of samples used to calculate input is 3
- **Do-While** same station type (action codes are the same)— Loop is executed at least once. For each time this loop is executed, one input to the fuzzy controller is calculated. (See rules for writing fuzzy equations in training manual for details.)
 - Get station:loop offset into RTDB from table
 - If action code is QUEUE or ADV_QUEUE
Get number of samples used to calculate input
 - If action code is HOV_BYPASS

Get percentage of HOV adjustment to lane

- For each sample needed to calculate input data
 - Calculate pointer to RTDB cabinet from station:loop offset
 - **unpack_rtdb_loop_stn data**
 - If data are good — This occurs when the number of loops is greater than 1 (meaning that it is a station, not a loop) and the flag is not equal to 0 (the station data are usable) OR if the number of loops is 1 (meaning that the data are loop data rather than station data) and the flag is 1 (the loop data are good). Note: These data have already been interpolated if it is necessary and possible
 - If action code is not DOWN
 - Increment number of good stations used to calculate this input
 - Increment number of total loops (over all stations) to calculate this input
 - Sum scan count
 - Sum volume to later calculate speed
 - Else action code is DOWN. (DOWN is handled differently than the other locations because it uses the maximum occupancy and associated speed rather than averaging all inputs)
 - If this occupancy is the maximum of the downstream occupancy inputs or if no other good data were found
 - Set number of good stations to calculate this input to 1

- Set number of total loops for all stations at this location to be the number of loops returned by **unpack_rtdb_loop_stn**
 - Set sum of scan count to the scan count returned by **unpack_rtdb_loop_stn**
 - Set sum of volume to the volume count returned by **unpack_rtdb_loop_stn**
- Set old action code to equal current action code
 - Get next action code
- End of do-while loop to process stations of same type
- If more than one station/loop are good, calculate controller inputs
 - Calculate average occupancy using scan count and total number of good loops
 - If location code < QUEUE (meaning that it is a mainline input)

Calculate average speed for that location using average volume and occupancy
 - Switch based on old action code (detector location)
 - In LOCAL or DOWN case, enter the calculated occupancy and speed in controller input array and store these inputs in global watch data set
 - In UP case,
 - Enter the calculated occupancy into controller input array for upstream input and store these inputs in global watch data set

- If there were no usable local data
 - Enter the upstream occupancy as the local occupancy and store this input in global watch data set
 - Enter the upstream speed as the local speed and store this input in global watch data set
 - Set data usable flag to YES
- In QUEUE or ADV_QUEUE case, enter the calculated occupancy in the controller input array and store these inputs in global watch data set
- In the HOV_BYPASS case, convert from vehicles summed over all samples to vehicles/minute and store this input in global watch data set
- Else (data for this location are insufficient to calculate inputs) — Check to see whether the lack of data at this location makes the rule base incomplete. If the rule base is incomplete, set the data_usable flag to NO so that local metering will be used instead.
 - Switch based on old action code (detector location)
 - In LOCAL case,

Set data usable to NO_LOCAL. (A complete rule base requires this input! Do not change this logic because the output of the fuzzy logic controller may not be undefined. The NO_LOCAL state differs from the NO state in that there is still the possibility that the upstream input

will be a good substitute for the local input. In this event, the data usable state would be returned to YES.)

- In DOWN case,

Set the rule weights to zero for the rules that use downstream inputs, (the rule base does not require this input for completeness)
- In UP case,

Set the rule weights to zero for the rules that use this input. (By default, this input is not used for upstream rules, but only as a substitute for the local data in the event they are bad).
- In QUEUE case,
 - Increase the advance queue rule weight by the queue rule weight to compensate for the bad data
 - Set the rule weight to zero for the rule that uses this input
- In ADV_QUEUE case,
 - If the queue weight was zero (this means that there are no usable ramp inputs), set the data usable flag to NO. (The fuzzy controller requires this input so that the resulting fuzzy metering rate is not too restrictive.)
 - Else (the queue input was OK), set the rule weight to zero for the rule that uses this input
- In HOV_BYPASS case,

Set the HOV bypass volume to zero. (With this, no HOV bypass adjustment will occur, which is not a problem.)

- End of while-loop to process a set (an equation for 1 metered lane)

- If data are usable to calculate the metering rate at this ramp (sufficient data set contains a local input and at least one ramp queue input)
 - **Calc_watch_fuzzy_rate** given the real-time data, fuzzification parameters, and rule weights
 - Do HOV bypass adjustment — subtract HOV bypass volume times the percentage of HOV adjustment for that lane from metering rate
 - If adjusted metering is smaller than fuzzy minimum metering rate
Set it to the fuzzy minimum metering rate
 - If the metering rate is greater than 25.5, it won't fit into 1 byte
Write diagnostic message to diagnostic message string and set diagnostic flag to YES
 - Convert the metering rate from a float to an unsigned character byte
 - Write the metering rate for that lane to watch data set (not to the RMDB)

- Else if data are not usable to calculate the metering rate at this ramp
Write diagnostic message to diagnostic message string and set diagnostic flag to YES

- Return the diagnostic flag

calc_fuzzy_rate — This function returns a metering rate given inputs to the fuzzy controller. *If the fuzzy ramp-metering algorithm were ported to other systems, this function and those that it calls would be used because they contain the fuzzy logic controller. All other functions interface the fuzzy logic controller with the TSMC and may be unique to this TSMC.*

- **Fuzzify** – Returns the fuzzy inputs given the crisp inputs and fuzzy parameters. This function translates each input into a set of five fuzzy classes.
- **Rules** – Evaluates the rules given the fuzzy inputs and rule weights. Returns the fuzzy metering classes.
- **Defuzzify** – Converts the fuzzy metering rates into a single numerical metering rate.

calc_watch_fuzzy_rate — This function is identical to **calc_fuzzy_rate** except that it calls **watch_rules** rather than **rules**.

- **Fuzzify** – Returns the fuzzy inputs given the crisp inputs and fuzzy parameters. This function translates each input into a set of five fuzzy classes.
- **Watch_rules** – Evaluates the rules given the fuzzy inputs and rule weights. Returns the fuzzy metering classes.
- **Defuzzify** – Given the fuzzy metering rates, returns a single numerical metering rate.

Fuzzify — Converts each numerical input into a set of five fuzzy classes, although some inputs do not use all five classes. For each input, it calculates the array of fuzzy classes that indicate on a scale of 0 to 1 the degree to which each class is true. *Note: By adjusting the Low and High parameters, the dynamic range of the class can be modified. We found that it was unnecessary to change the relative base width and relative positioning between the fuzzy classes. Thus, inputs use the compiled defaults for the triangle base widths and normalized centroids. If you find the need to modify the relative positioning or relative shape of the fuzzy classes for an input, this can be done in `calc_fuzzymeter` and `calc_watch_fuzzymeter`. For further details regarding how to adjust these classes, see the training manual, Taylor and Meldrum, 2000.*

- For each input
 - If high dynamic limit is lower than the low dynamic limit
Write error message with `log_tms_event`
 - Normalize the raw input from the parameter (Low, High) range to the (0,1) range.
All calculations internal to the fuzzy logic controller are performed on the normalized scale to simplify calculations. In defuzzify, the resulting normalized metering rate is rescaled to the (MeterRateLow, MeterRateHigh) range.
 - Calculate very small fuzzy class. The class is 1 if the rescaled input is less than 0. The class is 0 if the rescaled input is greater than the base width for the very small class. In between, it's a linear relationship.
 - For small, medium and big classes,
Calculate fuzzy input — It's a triangular class

- Calculate very big fuzzy class — The class is 1 if the rescaled input is greater than 1. The class is 0 if the rescaled input is greater than 1 minus the base width for the very big class. In between, it's a linear relationship

Rules — Evaluate each rule and return a set of five fuzzy classes for the metering rate given the fuzzy inputs and rule weights.

- Evaluate each rule given the fuzzy input. The degree of the rule outcome is equal to the degree of activation of the rule premise. (A logical AND between two premises takes the minimum of degrees in the premise.)
- Multiply each rule outcome by its rule weight
- Calculate the weighted sum of rule outcomes for each class to get the aggregated metering fuzzy classes

Watch_rules — Identical to **rules** except that it stores the rule outcomes in watch data set to be displayed by **watch_fuzzymeter**

- Evaluate each rule given the fuzzy input. The degree of the rule outcome is equal to the degree of activation of the rule premise. (A logical AND between two premises takes the minimum of degrees in the premise.)
- Store rule outcomes in watch data set
- Multiply each rule outcome by its rule weight
- Calculate the weighted sum of rule outcomes for each class to get the aggregated metering fuzzy classes

Defuzzify — Use discrete fuzzy centroid to convert set of fuzzy metering rates to a single numerical metering rate given the aggregate fuzzy metering rate classes and the parameters for the metering rate classes.

- For each fuzzy class of metering rate
 - Calculate the implicated area of the fuzzy rule outcome. (See documentation in the training manual for details. This is the fuzzification process in reverse.)
 - Calculate the centroid of the implicated area of the fuzzy class
 - Accumulate numerator sum for the discrete fuzzy centroid— the area of fuzzy class times the centroid of fuzzy class times the sum of weighted rule outcomes for that class
 - Accumulate denominator sum for discrete fuzzy centroid — the area of fuzzy class times the sum of weighted rule outcomes for that class
- If the denominator is too small

Write error message with **log_tms_event**

- If MeterRateHigh is not greater than MeterRateLow for the metering rate dynamic range limits

(Note: The resulting metering will be inside these limits because the centroid of the end triangles is inside the Low and High limits by 1/3 of the base width.)

Write error message with **log_tms_event**

- Calculate the metering rate = num/den and rescale from the (0,1) range to the (Low, High) range
- If metering rate is not within the (Low, High) range

Write an error message with **log_tms_event**

- Return metering rate

Fuzzy.h

Fuzzy.h contains definitions, structures, function prototypes, and compile options for fuzzymeter and watch_fuzzymeter. The compile options FUZZY_DEBUG, FUZZY_LOG, METER_LOG, and OBSERVE_ONLY warrant discussion.

The FUZZY_DEBUG option is no longer supported in the source code. It was used to create a test version of fuzzymeter. The test version of fuzzymeter read the fuzzy_meter.eqn file and built the fuzzy table in memory. This debug version was a useful tool for finding bugs in parsing the file or building the table. It conveniently stood alone and had no impact on operations because it did not calculate metering rates. For programmers who make future additions or modifications to a database or to TAPS, this technique is recommended.

The FUZZY_LOG option is supported in fuzzymeter.c and fuzzymeter_sub.c. If FUZZY_LOG is defined, a logging version of fuzzymeter.exe will be created. It will log the inputs, fuzzy classes, rule outcomes, and resulting metering rates for all fuzzy enabled (with PermitFuzzyMr) ramp meters to a file called fuzzymeter.log. Although this logging capability works, this version would produce TAPS time-outs now that we have so many ramp meters using fuzzy metering, preventing the fuzzy metering rates from being calculated and implemented in the allowable time. Thus, it is not recommended that this option be used because of the additional CPU that it requires. If you find that you need this capability, the logging technique would need to be rewritten in a fashion similar to that of **log_tms_event**, in which the message is put on a queue to be handled. This capability was originally created in anticipation of the need for off-line analysis of

the internal calculations of fuzzymeter in order to optimize its performance. We found that we did not need this capability to the extent expected because of the capabilities of watch_fuzzymeter. Through watch_fuzzymeter, we were able to observe all of these data real-time and optimize the performance of fuzzymeter.

If METER_LOG is defined, a version of fuzzymeter.exe will be produced that logs the cabinet name, lane status, and the metering rates as returned from the 170 by all actively metered cabinets to a file called meter.log. Although this capability worked fine prior to implementing system-wide with fuzzy metering, at this time, it is expected that this option may require more time to execute fuzzymeter than it is allocated. For this reason, it is not recommended that this option be used because it may prevent fuzzy metering rates from being implemented properly during TAPS time-outs. If you find that you need this capability, the meter logging capability would need to be rewritten in a fashion similar to that of **log_tms_event**, in which the message is put on a queue to be handled. However, if the reason you want the 170-returned metering rates is for analytical purposes, you may be better off using the passage rate instead (which can easily be retrieved through CDR). The passage rate is the *effective* metering rate.

If OBSERVE_ONLY is defined, a version of fuzzymeter.exe will be produced that does not execute the metering rates produced by fuzzy metering. We found this option to be invaluable for initial deployment of the Fuzzy Logic Ramp Metering Algorithm. With this option, we were able to compare the rates produced by the Fuzzy Metering Algorithm to those produced by other ramp metering algorithms given the same real-time data. We were able to do initial tuning with this technique without impacting operations in any way. However, the usage of this compile option is no longer recommended. When this option is used, no fuzzy metering rates are executable on the

system. Because many ramps have not been thoroughly tested for any other algorithms, operations would suffer from the non-optimal metering rates produced by other ramp metering algorithms.

Configuration Management

MMS files (VMS makefiles) were created for all TMS executables (Table 10). With the new MMS files, maintenance of the proper configuration is feasible. For all MMS files, executables can be produced in a bubble environment by redefining TMS_CODE and TMS_RUN (see Integration Procedure).

Table 10. Summary of New MMS Files for Configuration Management

Tms_lib.mms	Updates object library for ccb_subs.c crack_fp_msg.c, dump_mem.c, event_log_sub.c, fddb_lib.c, find_first_last.c, fmdb_lib.c, format_db_lib.c, format_el_msg.c, global_sub.c, intlk_queue.c. kb_func.c, link_sub.c, logical_name.c, mailbox.c, pack_lib.c, proc_cntrl.c, rtdb_lib.c, sched_lib.c, skel_sub.c, table_sub.c, tap_sub.c, tt_func.c, uaf_sub.c, utility_func.c, vms_lib.c, tms_comm_sub.c, misc_func.c, sort_lib.c, add_64.mar, bit_test.mar, calc_crc_16.mar, jhcbdef.mar, jhbfdef.mar, find_driver.mar, switch_driver.mar, init_driver.mar, driver_connected.mar
Cctvdb.mms	Updates build_cctvdb.exe, patch_cctvdb.exe, test_cctvdb.exe, del_cctvdb.exe
Gblldb.mms	Updates build_gblldb.exe, patch_gblldb.exe, test_gblldb.exe, del_gblldb.exe
Gcdb.mms	Updates build_gcdb.exe, patch_gcdb.exe, test_gcdb.exe, del_gcdb.exe
Oprtvdb.mms	Updates build_oprtvdb.exe, patch_oprtvdb.exe, test_oprtvdb.exe, del_oprtvdb.exe
Rmdb.mms	Updates build_oprtvdb.exe, patch_oprtvdb.exe, test_oprtvdb.exe, del_oprtvdb.exe
Scheddb.mms	Updates build_rmdbdb.exe, patch_rmdbdb.exe, test_rmdbdb.exe,

	del_rmdbdb.exe
Vaxportdb.mms	Updates build_vaxportdbdb.exe, patch_vaxportdbdb.exe, test_vaxportdbdb.exe, del_vaxportdbdb.exe
Vmsdb.mms	Updates build_vmsdbdb.exe, patch_vmsdbdb.exe, test_vmsdbdb.exe, del_vmsdbdb.exe
Wfmdb.mms	Updates Wfmdb.exe
Wrtdb.mms	Updates Wrtdb.exe
Rt.mms	tms_startup.exe, tms_shutdown.exe, build_fmdb.exe, build_rtdb.exe, Updates dumydata.exe, event_logger.exe, fmdb_aggr.exe, fmdb_archiver.exe, build_rtdb.exe, dumydata.exe, event_logger.exe, fmdb_archiver.exe, rt_skeleton.exe, stn_aggr.exe, fuzzymeter.exe, watch_fuzzymeter.exe, bottleneck.exe, actv_anal.exe, inc_detect.exe, snap_loop_err.exe
Noaa_monitor.mms	Updates noaa_monitor.mms
Upi_xmit.mms	Updates upi_xmit.mms
Opc_comm.mms	Updates multi_opc_comm.exe and test_opc_comm.exe
Rmdc_comm.mms	Updates multi_rmdc_comm.exe and test_rmdc_comm.exe
Vms_comm.mms	Updates multi_vms_comm.exe and test_vms_comm.exe
Util.mms	Updates crack_fmdb_dailyfil.exe, crack_fmdb_namefile.exe, crack_fmdb_snapshot.exe, watch_bottleneck.exe, watch_fmdb.exe, watch_rmdc.exe, watch_actv_anal.exe, and mon_event_log.exe

Tmsuw.mms	Updates tmsuw.exe
Tmsuw.opt	Links in libraries needed for tmsuw.exe
Get_20_sec.mms	Updates Start_20_sec.exe, Get_20_sec_data.exe, Edit_20_sec.exe, Crack_20_sec_data.exe, Test_20_sec_data.exe
Tms.mms	Updates all executables.

Edit_20_sec.c

Edit_20_sec.exe was created for users who wish to automatically collect specified 20-second data for weekday metering periods. This process automatically checks the time in order to know when to execute start_20_sec, which starts get_20_sec_data. To use this, the user must specify the desired collection times and desired loops/stations for the morning data in “am.input.” The user must specify the desired collection times and desired loops/stations for the afternoon data in “pm.input.” Using this information along with the current time and date, edit_20_sec automatically rewrites get_20_sec_data’s input file with the date, start time, stop time, and data to collect for each metering period. At this time, files produced are written to the test executable directory in taylorc’s account. However, extensive usage of this software would require the implementation of some data file management, which was beyond the scope of this project.

Prior to this project, the 20-second data collector was not usable because WSDOT could not interpret the binary files produced. Although the Washington State Transportation Center (TRAC) contracted HNTB to write software to utilize these binary files, WSDOT subsequently lost the executable that did this interpretation. (It would probably be fairly easy to rewrite this software.) In this project, we made a slight modification to get_20_sec.c to create a usable version of get_20_sec.c With a simple definition of GET_20_LOG, get_20_sec.c now produces ASCII data files. Because get_20_sec.c and start_20_sec_data.c were not previously documented, they are outlined here.

Get_20_sec.c is started from start_20_sec_data.c, which stands alone. In start_20_sec_data.c, **start_process** calls SYS\$CREPRC to start main get_20_sec. Get_20_sec reads the desired stations from input file “get_20_sec_data.input.” If GET_20_LOG is defined, it writes to an ASCII log file. (A sample ASCII file name is 980827_095300_20_SEC.LOG.) If defs have been added to specify whether to write to a binary data file. (A sample binary file name is 980827_095300_20_SEC.DAT.)

Start_20_sec_data calls the following functions:

- **Connect_to_mailbox**
- **Map_to_RTDB**
- **Load_get_20_name_table**
- **Calc_num_data_blocks**
- **Check_date_time**
- **Read_get_20_input_file**
- **Write_file_header**
- **Dump_file_header** — writes to log file
- **Dump_get_20_name_table** — writes to log file
- **Collect_20_sec_data**

Get_20_sec_sub.c calls the following functions:

- **Dump_file_header** — prints file header to output file
- **Dump_get_20_name_table** — prints name, type, size, and offset of data to output file

- Fprintf(out_file, "%16.16s %02x ", name_ptr->name, type);
- Fprintf(out_file, "[LOOP]") or Station, speed trap, etc
- Fprintf(out_file, " %8d", rtdb_offset[i]);
- **Crack_date_time_stamp** — prints beginning month, day, year, hour, minute, second to output file. Called from collect_20_sec_data. Prints end month, day, year, hour, minute, second to output file in the following format:

```
02d/%02d/%04d+%02d:%02d%:%02d->%02d:%02d:%02d\n"
```
- **Crack_rtdb_data** — prints data to output file. Called from **collect_20_sec_data** and writes data in the following format:

```
Fprintf(out_file, " %16.16s %02x ", name_ptr->name, type);
```

```
Fprintf(out_file, " %16.16s %02x ", name_ptr->name, type);
```

```
Fprintf(out_file, "V=%3d S=%4d O=%5.1f F=%d I=%d n=%d\n",
```

```
volume, scan_count, occupancy, flag, inc_det, n_loops);
```

Sample output of log file, not including headers

09/01/1998+14:31:40->14:31:59

ES-TD4R:MMN__1 50 [LOOP]V= 0 S= 0 O= 0.0 F=0 I=0 n=0

ES-TD4R:MMN__2 50 [LOOP]V= 0 S= 0 O= 0.0 F=0 I=0 n=0

ES-TD4R:MMN__3 50 [LOOP]V= 0 S= 0 O= 0.0 F=0 I=0 n=0

ES-TD4R:_MNLA_1 50 [LOOP]V= 0 S= 0 O= 0.0 F=0 I=0 n=0

ES-TD4R:_MN_I_1 50 [LOOP]V= 0 S= 0 O= 0.0 F=0 I=0 n=0

SOFTWARE TESTING

Because no major changes had been made to the original source code prior to the implementation of the Fuzzy Logic Ramp Metering Algorithm, it was necessary to develop a procedure to do this. With a critical real-time system such as the TMS software, it was important to integrate the software in such a way as to minimize the risks of TMS downtime, software bugs, and configuration management problems. Software quality tests were developed and used to verify that the software retained its old functionality while performing its new functionality.

INTEGRATION PROCEDURE

The quality of new and modified software was thoroughly tested prior to on-line implementation to reduce the risk of bugs. We did this by first testing the software on a separate microVAX computer that had duplicate software running in real time, but was unconnected to any field devices. In gradual steps toward implementation on the real-time system, we used a “bubble environment” in which the original executables were undisturbed and could always be recreated, and the new executables were always created with the latest source code. In this manner, the risk of the new software was minimized because we could always return to the old software.

With multiple programmers working on various aspects of the code, it was essential that we never produced executables from incompatible versions of the source code. To prevent problems with configuration management, we assigned domains to each programmer. Lanping Xu was assigned to system administration, `opc_comm` and to entering the files into CMS once they had passed all software tests. Harriette Lilly was assigned to `vms_comm` and `vmsdb`. Cynthia Taylor was assigned to `rt_skeleton`, `rmdb`, and `rmdc_comm`. Mark Morse was assigned to the 170 code. If programmers wanted to alter code outside their domain, they had to do it through the programmer of that domain.

With this technique, we were aware of any code incompatibility issues. We coordinated our implementation and testing schedules through daily communication. This degree of coordination was necessary because of the sharing of test beds and the necessity that only one programmer implement changes at a time. We only implemented one programmer's changes at a time in order to discern the cause of any problems that arose and to prevent improper software configurations.

With these risk management issues in mind, the following software integration procedure was developed:

- 1) Develop a list of regression tests to be performed that verify that the new software still has the functionality of the old software.
- 2) Develop a list of tests to verify the new functionality of the software.
- 3) Perform a file comparison between the new source code and the current source code from which the executables that are currently operating on the real-time system were created. Merge the changes with the current source code to prevent any software configuration problems.
- 4) Create a test code directory in which only the new or modified files reside. Define the TMS_CODE path name such that the compiler first searches in the test directory for the source code, and then searches in the official source code directory if it cannot find the file in the test directory. In this manner, the executables will be created from the latest files, reducing the risk of software configuration problems. Another advantage of this "bubble" environment is that the original executables can always be reproduced from the old source code by redefining the tms_code path.

- 5) Copy the MMS files (VMS makefiles) into the test code directory. Change the specification of the executable directory from TMS_RUN to TMS_PRIMAL. With this technique, the new executables are placed in their own test directory, TMS_PRIMAL. In the event of a software problem, the system can be restarted from the unaffected original executable, TMS_RUN.
- 6) Compile the code described in the bubble environment of steps 3-5 to produce the new executables.
- 7) Copy the executables produced in step 6 to a separate test computer that duplicates the real-time environment. We used a microVAX for this, complete with a TMS console and test 170.
- 8) Perform the tests in steps 1-2 to verify the software quality.
- 9) If there are no errors in step 8, run the new executables in the TMS_PRIMAL directory on the real time system. If a problem is encountered, the original system can be restarted from the TMS_RUN directory.
- 10) Perform the tests in steps 1-2 to verify the software quality.
- 11) If there are no problems with step 10, check in the new source code with the Configuration Management Software (CMS). This procedure will put the new source code into the current source code directory. At this point, the bubble environment of steps 3-5 is no longer necessary. Compiling directly from the source code directory will produce the new executables in the tms_run directory.

We used this procedure both for the implementation of the Fuzzy Logic Ramp Metering Algorithm and for the implementation of new VMS communications protocol. The procedure was highly successful. We did not have any downtime due to the

implementation of the Fuzzy Logic Ramp Metering Algorithm, nor did the new code from this project cause bugs that impacted operations.

Once the software quality had been established, fuzzymeter was field tested in a procedure with gradual steps toward full deployment. A compile feature of fuzzymeter called observation mode (see fuzzy.h) allowed us to produce fuzzy metering rates based on real-time field data and observe the fuzzy metering rates without implementing them. With this feature, we compared the fuzzy metering rates to the metering rates produced by the other ramp metering algorithms. This feature proved to be very useful: we were able to do preliminary tuning of the fuzzy ramp-metering algorithm prior to field deployment. For further details of the field-testing plan, see the “Evaluation of a Fuzzy Logic Ramp Metering Algorithm: A Comparative Study Between Three Ramp Metering Algorithms used in the Greater Seattle Area” (Taylor and Meldrum, 2000).

RESULTS OF REGRESSION TESTING

Regression testing was performed to ensure that no old functionality was lost with the new software changes. The regression testing encompassed all processes on the VAX, including rmdb, build_all_db, fmdb, rtdb, rmdc, rmdc_comm, opc_comm, vms_comm, noaa_monitor, cctv, mon_event_log, log files, incident_detect, and tmsuw. All tests achieved the desired result.

Rmdb

The following tests were successfully performed on the new RMDB software to verify the old functionality of the RMDB:

- 1) Viewed RMDB from **patch_rmdb** and verified that all values were displayed correctly.

- 2) Verified that compiled defaults appeared correctly on the TMS console after start-up. The parameter values correctly matched the compiled defaults in the cases where they were not overridden in the rmdb_input.fil
- 3) Verified that parameters in rmdb_input.fil were correctly updated in the database, overwriting the compiled defaults as intended.
- 4) Verified that we can change a value from patch_rmdb.
- 5) Verified that all 287 columns were successfully displayed from patch_rmdb.

Build all db

We verified that all equations were created correctly when building all databases with the new software. We compared the equations produced by the new software in the TMS_PRIMAL directory to those created by the old software in the TMS_RUN directory when given identical input files. The output files produced (including actv_anal.eqn, inc_det.eqn, stn_aggr.eqn, and btl_neck.eqn) were identical between the old and new software.

Fmdb

- 1) Compared the 5-minute aggregation using the new and old versions of watch_fmdb. All 287 Ramp Meter/Data Collectors were shown with the new watch_fmdb, and the data were the same for both versions.
- 2) Watch_fmdb was used to check station aggregation on the following test cases:
 - ES-710R:_MN_Stn=_MN___1+_MN___2+_MN___3
The station volume = $120+102+124 = 346$. The hand calculation matched that shown in watch_fmdb.
 - ES-710R:MMS_Stn=MMS___1+MMS___2+MMS___3

The station volume = $102+124+117=343$. The hand calculation matched that shown in watch_fmdb.

- 3) Used wfmdb.exe to verify that data looked valid.
- 4) Tested the validity of archived data. Compared real time data viewed with watch_fmdb for loops, stations, and speed traps with the archived data viewed from CDR. For ES-516R at 13:10, there were no discrepancies. Compared real-time data viewed with wfmdb for loops, stations, and speed traps with the archived data viewed from CDR. For ES-726R at 12:55, there were no discrepancies.

Rtdb

- 1) Checked the accuracy of 20-second station aggregation, using wrtdb.exe to observe the loop and station data.
 - ES-710R: $\text{MN_Stn} = \text{MN}___1 + \text{MN}___2 + \text{MN}___3$
Station volume = $8+10+6=24$. Wrtdb matched the hand calculation.
Station occupancy = $(6.8+12.1+12.5)/3=31.4/3=10.5$ Wrtdb matched the hand calculation.
 - ES-710R: $\text{MMS_Stn} = \text{MMS}___1 + \text{MMS}___2 + \text{MMS}___3$
Station volume = $8+9+11=28$. Wrtdb matched the hand calculation.
Station occupancy = $(15.6+10.1+13.3)/3=39.0/3=13.0$ Wrtdb matched the hand calculation.
- 2) Verified that the 170s returned the data correctly and that the data were properly placed into the RTDB.

- 3) Verified that the FLOW map on the WSDOT web page properly received the data.

Rmdc

We conducted tests to verify the proper operation of the metering algorithm through the use of watch_rmdc, TMS, and the 170 test rack:

- 1) We verified that the local algorithm worked properly when no queue override conditions were present. The proper local lane status and other metering data appeared on the operator console. The 45th St. southbound ramp was metering at 16.0 VPM when the mainline occupancy was 15% and the mainline speed was 33 MPH.
- 2) We verified that the local algorithm worked properly when queue override conditions were present. The override lane status appeared in the TMS console for lanes 1, 2, and 3 when the 170 test rack's queue occupancy value exceeded the queue occupancy threshold for the necessary time duration.
- 3) We verified that the local algorithm worked properly when the advance queue override conditions were present. The advance override lane status appeared in the TMS console for lanes 1, 2, and 3 when the test rack's advance queue occupancy value exceeded the advance queue occupancy threshold for the necessary time duration.
- 4) We verified that the volume adjustment occurred when the passage rate exceeded the metering rate on the test rack, causing the metering rate to remain at its minimum metering rate of 5 VPM.

Rmdc comm

We tested the old functionality of rmdc_comm, which involves communications between the VAX and 170.

- 1) We verified that Lane Parameters 1, 2, and 3 were sent to the VAX through opc_comm when they were updated in TMS. The new parameters were then sent to the 170 test rack through rmdc_comm.
- 2) Using test_rmdc_comm, we verified that the VAX sent the date/time message properly to the 170 upon startup and that an acknowledgment was returned by the 170.
- 3) Using test_rmdc_comm, we verified that the reset command was properly sent to the VAX from the 170 and that the 170 responded with an acknowledgment.
- 4) Using test_rmdc_comm, we verified that the data poll was properly sent from the VAX to the 170 upon startup and that the VAX successfully received the data returned from the 170. These returned data were displayed correctly in the TMS console.
- 5) Using test_rmdc_comm, we verified that the VAX properly sent the error request and that in turn, the VAX successfully received the error data returned from the 170.
- 6) We tested the start and stop metering command from the operator console and verified the 170's proper execution using CCTV.

Opc comm

We verified proper communication between the operator consoles and the VAX through the following tests:

- 1) We verified that all parameters are viewable and updateable from the operator console. The new values were downloaded to the 170 and continued to be displayed correctly on the operator console when it refreshed the screen.
- 2) Parameter changes made from the operator console properly appeared in the rmdb_journal.fil.
- 3) A pass report was sent out to NOAA and to the WSDOT Web page. It reached NOAA and the Web page successfully.
- 4) The ability for the operators to send messages to each other via TMS was tested. A test message was sent to the four operators currently logged on, and the window displaying the message appeared correctly on their consoles.
- 5) We tested the operator incident messaging and verified that it was correctly displayed on WSDOT Web page.

Vms comm

We tested the commands sent to the variable message signs (VMS) from the operator console.

- 1) We sent out the VMS message “Traffic Conditions (206) 368-4499” to sign VMS-887. We verified the display with a CCTV camera.
- 2) We then blanked the sign and verified it with the CCTV.
- 3 We switched the message to “Ride Share Info” and verified it with the CCTV camera.
- 4) We successfully created a new sign cluster.
- 5) We created a new message within this cluster. The changes were journaled correctly in vms_journal.fil.

Noaa monitor

Two tests were completed to verify proper communications between the VAX and NOAA:

- 1) We tested that a pass report reached NOAA successfully.
- 2) We tested that the NOAA reports reached us successfully.

Cctv

We checked all camera operations.

- 1) We assigned the monitor to the camera on I-405 at NE 116th St, swiveled it around, zoomed in and out, and focused without any problems. Then we switched the display to the camera at I-90 at 4th Ave southeast bound.
- 2) We viewed up-to-date camera images on WSDOT's Web page.

Mon event log

We monitored the events as we ran tms_startup in the directories with the old and new executables. There were no discrepancies. Although there were some minor errors, these errors had pre-existed and were identical between the two versions of software.

Log Files

All output files of the new code were compared to those produced by the old code. The output files consist of the operator log file, the tms event log file, the rmdc comm log file, the opc comm log file, the vms comm log file, the tms crash log, the FMDB daily primary files, the FMDB snapshot primary files, and the database journal files.

- 1) The *operator log* was created and written successfully. No errors were reported. All operations were logged correctly into the file OPERATOR_011999.LOG;2 on 19-JAN-1999 12:25:26.60.
- 2) The *tms event log* file, TMS_EVENT_990119.LOG;2, was created successfully on 19-JAN-1999 12:24:17.84. No errors appear in the event log. Normal operations are logged correctly. The log files created by the old and new executables were compared. The only difference was that upi_xmit had a busy phone line in the event log file of the old software. The VAX output is shown below:

TMS Event File Created - 01/19/1999 12:24:17.77

```

-----
12:24:18.09 09008013 EVENTLOG Startup:ersion 0.25 - 04/29/94
12:24:21.05 00000000 MONEVTLG Start MON_EVENT_LOG Echo
12:24:24.80 08230003 UPI_XMIT Version 0.19 - 04/29/94
12:24:24.88 00000000 UPI_XMIT Warning-UPI Port DISABLEd, set to ENABLE
12:24:25.04 0822800b NOAA_MON Version 0.20 - 04/29/94
12:24:25.38 08220003 NOAA_MON Warning-NOAA Port DISABLEd, set to ENABLE
12:24:25.38 08228013 NOAA_MON Startup Complete
12:24:25.40 0808800b BLD_RTDB Version 0.19 - 04/29/94
12:24:25.42 00000000 BLD_RTDB Existing global section - Delete it
12:24:25.93 00000000 BLD_RTDB Global Section Created-size=3284980
12:24:30.14 0809800b BLD_FMDB Version 0.28 - 04/29/94
12:24:30.18 00000000 BLD_FMDB Existing global section - Delete it
12:24:31.13 00000000 BLD_FMDB Global Section Created-size=5667673
12:24:52.65 08230003 UPI_XMIT Startup Complete
12:25:20.53 080e800b DUMYDATA Version 0.30 - 04/29/94
12:25:20.64 080e8013 DUMYDATA Startup Complete
12:25:20.82 080f800b STN_AGGR Version 0.22 - 04/29/94
12:25:21.11 0810800b INC_DET Version 0.29 - 04/29/94
12:25:21.27 08108013 INC_DET Startup Complete - table_size = 18
12:25:21.38 0811800b BTL_NECK Version 0.24 - 04/29/94
12:25:21.56 08118013 BTL_NECK Startup Complete-table_size=128
12:25:22.02 080f8013 STN_AGGR Startup Complete-table_size=10006
12:25:22.26 0824800b FUZZY_MR Version 0.25 - 10/23/98
12:25:22.33 08248013 FUZZY_MR Startup Complete-table_size=18
12:25:22.51 0820800b FMDBAGGR Version 0.31 - 12/23/96
12:25:22.62 08208013 FMDBAGGR Startup Complete
12:25:22.78 0821800b FMDBARCH Version 0.22 - 04/29/94
12:25:23.07 0900800b RT_SKEL ersion 0.31 - 06/03/98
12:25:23.94 08218013 FMDBARCH Startup Complete
12:30:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
12:31:01.77 00000000 MONEVTLG Terminate MON_EVENT_LOG Immediately
12:40:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999

```

```

12:50:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:00:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:08:09.51 00000000 MONEVTLG Start MON_EVENT_LOG Echo
13:10:00.09 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:20:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:30:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:30:03.85 00000000 MONEVTLG Stop MON_EVENT_LOG Echo
13:40:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:50:00.00 00000000 EVENTLOG 10 Minute Time Stamp: Date = 01/19/1999
13:58:06.83 00000000 SHUTDOWN TMS_SHUTDOWN Started
13:58:06.85 08230003 UPI_XMIT Terminating
13:58:06.85 00000000 NOAA_MON stop_noaa_port() called
13:58:06.85 08220003 NOAA_MON Terminating
13:58:13.00 00000000 RT_SKEL Polling Process Timeout
13:58:13.00 00000000 RT_SKEL MULTI_RMDC_COMM Failed to Complete
13:58:22.00 00000000 RT_SKEL Start TMS Shutdown Sequence
13:58:22.00 00000000 EVENTLOG SHUTDOWN Bit Set
13:58:22.03 080e8023 DUMYDATA Terminating
13:58:23.02 080f8023 STN_AGGR Terminating
13:58:23.02 08108023 INC_DET Terminating
13:58:23.04 08118023 BTL_NECK Terminating
13:58:23.27 08248023 FUZZY_MR Terminating
13:58:23.39 08208023 FMDBAGGR Terminating
13:58:23.43 00000000 RT_SKEL Terminating
13:58:24.02 08218023 FMDBARCH Writing Snapshot Files at Termination
13:58:24.69 08218023 FMDBARCH Writing Daily Files at Termination
13:58:39.85 08218023 FMDBARCH Terminating
13:58:39.88 00000000 EVENTLOG Terminating

```

TMS Event File Closed - 01/19/1999 13:58:39.88

- 3) The **rmcdc comm log file** was successfully created and written: **RMDCCOMM_M.LOG;1218** on 19-JAN-1999 12:25:25.09. In both the new and old software, all units were set to comm active upon startup. Most of the ports operated successfully. In the cases where a port had a problem, the same port had the same problem when the system was restarted with the other code. For example, the following error message occurred on the same ports in both log files:

```

13:46:52.00 0813013a ES-662R: No response to DATA_POLL
13:46:50.79 08130193 ES-662R: Possible Run-Away Port-cc=0000018c
13:01:24.30 0813023b ES-TR6R: Unit set to COMM_MARGINAL
12:26:05.04 0813022b ES-TR6R: Unit set to COMM_FAILURE
12:59:25.01 08130213 ES-TR5R: Unit set to COMM_ACTIVE
13:48:23.93 08130053 ES-156R: Data Checksum Error

```

In both instances, there was a higher than expected occurrence of the data checksum error. We believe that this frequency of occurrence was caused by a bug that still exists in the 170 chip. Although the 170 returns the correct data, the checksum error is calculated before the final data are written, causing the checksum error. Because this error occurred frequently on both the TMS_PRIMAL and TMS_RUN executables, we do not believe this possible bug is related to the new code.

- 4) The *opc_comm log file* OPC_COMM_M.LOG;341 19-JAN-1999 12:25:26.07 was created and written successfully. Several errors occurred in this log. However, all of the same errors also appeared in the *opc_comm log* created by the old executables. Thus, we do not expect any of these errors to be caused by the new code. Below is a sampling of the events that occurred:

OPC_COMM Log File Created - 01/19/1999 12:25:25.34

```
-----
12:25:26.82 00000000 OPC_COMM Version 0.160 - 03/03/97
12:25:29.33 08150003 WSP_BLV: In assign_initial_camera()-Camera name [CCTVMS1] not found
12:25:29.61 00000000 OPC_COMM start_next_tms_sched():First Entry < Current Time
12:25:29.72 00000000 OPC_COMM Startup Complete
12:25:46.11 00000000 TMS_P2R: User NOT Logged In-Cmd=52
12:25:48.67 08120003 TMS_P2R: Port/Unit set to COMM_ACTIVE
12:25:56.44 08120003 O_TXF0: No Stn for ES-116R 5 Pike St-REV 2 for handle 8001
12:25:57.89 00000000 TMS_P2R: Invalid command in TxDoneRx=4e
12:25:58.94 00000000 INTRNET: Timeout - Device did not respond
12:25:58.94 08120003 INTRNET: Buffer queued for re-transmission
12:26:28.64 00000000 TMS_A_L: User NOT Logged In-Cmd=52
12:30:32.43 08120003 TMS_P2R: Error status from Driver (TxDone)-cc=0000022c
12:30:32.43 08128003 TMS_P2R: Error from SYS$QIO(SendTx)-cc=000002c4
12:30:32.43 08120003 TMS_P2R: Fatal Driver Error-cc=000002c4
12:30:32.68 00000000 TMS_P2R: Unexpected ACK received - Ignored
12:34:51.95 08120003 O_TXE0: In process_loginout()-SlaveConsole not found
12:43:42.53 08120003 MS_D6 : RTDB Name(s) for handle 0005 not found
12:47:20.03 08150003 MS_D6 : In switch_monitor_to_camera()-Invalid Camera Unit No=0
12:52:37.65 08120003 TMS_P2R: VMSDB Element V{VMS-877}*ROAD&LOCATION for
handle 7100 not found
13:55:30.52 081f0163 O_TXB3: Port Inactive - Status set to ENABLE
```

13:57:03.85 00000000 MB_TNL : Timeout - Device did not respond
13:57:03.85 08120003 MB_TNL : Port/Unit set to COMM_MARGINAL due to Hard Error
13:57:03.85 08120003 MB_TNL : Error limit exceeded-TxWaitRx comm aborted

- 5) The vms comm log file was created VMS_COMM_M.LOG;205 on 19-JAN-1999 12:25:25.40. All of the messages in this file were similar between the old and new software.
- 6) There were no discrepancies in the tms crash log between the old and new software. The output is below:

```
12:25:28.79 OPC_COMM:log_comm_event():Invalid mpu_no-cc=10000023  
12:25:29.03 OPC_COMM:Warning-Video Switch Port DISABLEd, set to ENABLE-  
cc=100000  
23  
12:25:29.72 OPC_COMM:log_comm_bfr():Invalid unit_no-cc=0000010b
```

- 7) The fmdb daily primary file was created successfully, 19990121.DAT;3 on 21-JAN-1999 14:31:16.55.
- 8) The FMDB snapshot primary files were successfully created every 5 minutes during operation of the new executables.
- 9) We verified that all database journal files were created and written successfully, including rmdb_journal.fil, vmsdb_journal.fil, scheddb_journal.fil, oprtvdb_journal.fil, gblldb_journal.fil, and cctvdb_journal.fil. The rmdb_journal.fil showed the parameters that we edited from the operator console. The vmsdb_journal.fil showed the new sign cluster that we created and the new test message that we added. It recorded our deletion of the new test cluster as well.

Incident Detect

We built the following incident detect equation:

ES-TR8R:MMN_Inc = ES-TR8R:MMN_Stn & ES-TD1D:_MN_Stn

We decreased the downstream occupancy to 10.5% using dummy data, and increased the upstream occupancy to 34.8% using the test rack. The incident was successfully detected. When we decreased the occupancy back down to 21.7%, the incident cleared as expected. Table 11 summarizes the events that occurred:

Table 11. Regression Test Results for Incident Detection

<u>TIME</u>	<u>OCC for ES-TR8R:MMN_Stn</u>	<u>INC STATE</u>
16:11:00	21.0%	NO INCIDENT
16:11:20	34.8%	TENTATIVE INCIDENT DETECTED
16:11:40	71.8%	INCIDENT OCCURRED
16:11:59	68.7%	INCIDENT_CONTINUING
16:12:19	69.6%	INCIDENT CONTINUING
.		
.		
.		
16:31:19	21.7%	NO INCIDENT

Tmsuw

We verified that TMSUW started up properly and that data were properly sent from the VAX to the University of Washington (UW).

- 1) TMSUW started up with no errors in tmsuw.log. (In the new software, tmsuw was added to tms_startup so that it would not need to be started independently.)
- 2) We examined the real-time 20-second data on the VAX using watch_rmhc, and we compared them to those received by UW in real time for the following locations: ES-726R on I-405, ES-900R on I-90, ES-159R on I-5, ES-516R on SR 520, ES-623D on SR 167. All data matched.

TEST RESULTS OF NEW FUNCTIONALITY

The new functionality of RMDB, fuzzymeter, watch_fuzzymeter, and the 170 chip was tested. The new processes were tested for Y2K compliancy. All tests were successful.

Build rmdb

The following tests were performed to verify the new functionality of the RMDB.

All tests achieved the desire result.

- 1) Compiled new rmdb_tbl.c, rmdb_sub.c, rmdb.h without errors.
- 2) Compiled new tok_tbl.c without errors.
- 3) Compiled and linked new build_rmdb.c, rmdb.h, rmdb_func_prot.h, tok_tbl.c, tap.h without errors.
- 4) Ran build_rmdb without yet using the new group names or new parameters.
Results were the same as before the software changes took place, as expected.
- 5) Added new group name [Fuzzymeter_Parameters] to rmdb_input.fil and verified that new group name was written to the screen and rmdb_error.fil without errors.
(Rmdb_error.fil contains more than just error messages.)
- 6) Added new group name [Fuzzymeter_Equations] to rmdb_input.fil and verified that new group name was written to the screen and rmdb_error.fil without errors.
- 7) Switched the order of the two new group names in rmdb_input.fil and verified that the switched order did not cause errors.
- 8) Changed the group name to lower case to verify that token parser changed it to upper case without any problem reading it.
- 9) Tested that the parser would catch the error of misspelled new group names. The error was successfully written to the screen and to rmdb_error.fil.

- 10) Tested each parameter name given an acceptable value in rmdb_input.fil. Note: parameter type USHORT1P requires an entry format of x.x% with a percent sign.
- 11) Tested the range limits for each parameter type. The parser correctly accepts values \geq minimum limit and values \leq maximum limit. The parser does not accept values outside of this range.
- 12) Added a fuzzy equation, which was successfully parsed and written to fuzzy_meter.eqn file.
- 13) In fuzzy equation, changed "FM1" to "Btl" in cab/loop name. The parser correctly produced the message, "Error — wrong equation type. Equation not written."
- 14) In fuzzy equation, changed "FM1" to "FM4" in cab/loop name. The parser correctly produced the message, "Error — Invalid char. Invalid cabinet/loop name. Equation not written."
- 15) In fuzzy equation, changed the cabinet name to be metered so that it does not match the current group name. Fuzzymeter correctly produced the message, "Error — cabinet name doesn't match current group name. Equation not written to file."
- 16) In fuzzy equation, put an extra character in cab/loop name. The parser correctly produced the message, "Error — Invalid char. Invalid cabinet/loop name. Equation not written."
- 17) In fuzzy equation, exceeded the allowable number of loops for each location type. The parser correctly produced the message, "Error — Too many loops of a location type. Equation not written to file."

- 18) In fuzzy equation, deleted the number of samples for the advance queue in fuzzy equation. The parser correctly produced the message, “Error — Number of samples for advance queue not given. Equation not written to file.” The next parameter following the faulty equation was parsed properly, as intended.
- 19) Deleted the second line of the fuzzy equation. The parser correctly produced the proper error message. The equation was not written and the next parameter after the equation was parsed properly.
- 20) Deleted the last line of the fuzzy equation. The parser produced the correct error message. The equation was not written and the next parameter after the equation was parsed properly, as intended.
- 21) In fuzzy equation, added a loop for the HOV bypass. (The HOV bypass loop is optional in the equation format). The loop was processed properly and the equation was written to file.
- 22) Changed the HOV bypass loop to a bad loop name by using "_Q" instead of "HP" in the fuzzy equation. The parser correctly handled the error with the message, “Error — Wrong loop type for HOV bypass. Equation is not written to file.”
- 23) Added a seventh loop location after the HOV bypass location in the fuzzy equation. The correct error message was produced, “Error — Too many locations. Equation not written.”
- 24) In fuzzy equation, removed the location queue, but still provided the HOV bypass location. This test verified that the parser did not try to use the optional HOV bypass location as a required location. The correct message was produced, “Error — Missing delimiter, equation expected to continue. Equation not written.”

- 25) In fuzzy equation, removed the advance queue location, but still provided the HOV bypass location. The correct error message was produced, “Error — Missing delimiter, equation expected to continue. Equation not written.”
- 26) Changed `|` delimiter to `%` in fuzzy equation. The correct message was produced, “Error — Delimiter of `|` or `&` expected. Equation not written.”
- 27) Changed `&` delimiter to `%` in fuzzy equation. The correct message was produced, “Error — Delimiter of `|` or `&` expected. Equation not written.”
- 28) In fuzzy equation, moved `|` from end of line to beginning of next line. (Note: To continue an equation on the next line, you must end the line in a delimiter.) The correct message was produced, “Error — Missing delimiter. Equation not written.”
- 29) Deleted a delimiter between stations. The correct message was produced, “Error — Missing delimiter. Equation expected to continue. Equation not written.”
- 30) Added extra spaces around delimiters to verify that this did not cause a problem. The equation was correctly written without errors.
- 31) Added extra space around the number of samples inside of the parenthesis to verify that this did not cause a problem. The equation was correctly written without errors.
- 32) Added extra space before the parenthesis containing the number of samples. (Note: Spaces are optional around the parenthesis.) The equation was correctly written without errors.
- 33) Left out a tab on a continued line of fuzzy equation. (Note: Tabs are considered white space and are optional.) The equation was correctly written without errors.

34) Continued a long equation line past 80 columns. The equation was correctly written without errors.

To summarize, several equation error checks are done when build_rmdb.exe runs to verify that the information given in rmdb_input.fil was correctly entered. If an error occurs during the rebuild, an error message is written both to the screen and to rmdb_error.fil (found in the executable directory). Table 12 lists the tests performed during the building of RMDB and the error messages generated. Quite often, more than one error message will be generated by a single error. Subsequent errors are common because the equation parser discards the remainder of the line when it finds an error in that equation. It searches for the beginning of the next equation and then produces errors when that line (often a continuation of the bad equation) does not resemble the beginning of the next equation. For this reason, first fix the first error listed (the real error) and then determine whether any errors persist on the next rebuild. Depending on how creative the user is with writing equations, it is possible that error messages other than the ones listed will occur. Table 12 lists the most probable error messages generated for a given event. (For further instructions on writing fuzzy equations, please see the training manual, Taylor and Meldrum, 2000.)

Table 12. Equation Error Checks Performed in Build RMDB

EQUATION CHECK PERFORMED	ERROR MESSAGE
Data Column type must be either a ramp meter or a data collector	"Fuzzy meter Eqn valid only for RM or DC"
Characters 13 and 14 must be the string 'FM'	"Wrong equation type — Must be FM for

	Fuzzy Meter”
Metered cabinet must match the current cabinet name	“Metered cabinet name doesn't match column name or bad fuzzy eqn continues”
The cabinet name to be metered must use the correct format	“Cabinet/loop name to meter is not valid in fuzzy eqn”
All detector names must use complete 15 character format, using the cabinet name, followed by a ':', then either the station or loop name (the parser does not assume current cabinet as in Bottleneck equations)	“Cabinet/loop name not found in fuzzy eqn” (The error check that this detector actually exists is not performed until later during tms_startup)
A detector name must be continuous within a line with no spaces in between	“Cabinet/loop name not found in fuzzy eqn”
The controller inputs must be given in the order of local, downstream, upstream, queue, advance queue, and HOV.	None—The parser might catch this error through a subsequent check, but has no way of knowing if the order is incorrect
The number of inputs (delimited by ' ') may not exceed six.	“Too many 's delimiting locations in fuzzy eqn”
Up to five loops/stations each are allowed for the Local, Queue and Advance Queue Inputs	“Too many loops of a station type in fuzzy equation”
Only one loop/station each is allowed for the Upstream and HOV sinput	“Too many loops of a station type in fuzzy equation”
EQUATION CHECK PERFORMED	ERROR MESSAGE
Up to 20 loops/stations are allowed for the Downstream input	“Too many loops of a station type in fuzzy equation”
' ' must be used to delimit different input types	“Missing delimiter — expecting ' & ' or ' ' to continue fuzzy eqn”
'&' must be used to delimit stations/loops of the same input type	“Too many 's delimiting locations in fuzzy eqn”
An equation to be continued on the next line must end with a delimiter '=', ' ', or '&'	“Missing delimiter — expecting ' & ' or ' ' to continue fuzzy eqn”
The HOV input is the only optional input.	“Missing delimiter in fuzzy eqn — expecting & or ” or “Queue or Advance Queue loops are missing from fuzzy eqn”
The number of samples used to calculate the Queue and Advance Queue inputs must be given in parenthesis following detector name, with no spaces in between.	“Number of samples for queue or percent adjustment for HOV not found in fuzzy eqn”
If there is not an HOV input, the equation must end with the Advance Queue input, followed by the number of samples —	“Cabinet/loop name not found in fuzzy eqn”

not a delimiter	
HOV loop must be a passage loop containing the string “HP”	“Loop for HOV Bypass in fuzzy eqn is not of correct type”
The percentage of HOV bypass applied to a lane must be specified in parantheses immediately after the HOV loop name	“Number of samples for queue or percent adjustment for HOV not found in fuzzy eqn”
The percentage of HOV bypass applied must be between 0 and 100	“Percent adjustment for HOV Bypasss is out of 0—100 range in fuzzy eqn”
Do not put more than one equation per line. (This differs from the other Traffic Analysis Programs.)	Either second equation will not be found or several possible messages will be generated if the second equation continues to the next line

Fuzzymeter

The following tests were performed to verify the operation of fuzzymeter and watch_fuzzymeter. All tests were completed successfully.

- 1) Rebuilt RMDB with fuzzymeter equations, error free.
- 2) The fuzzymeter parameters appeared in patch_rmdb and could be updated successfully.
- 3) Tested that fuzzymeter obtained the correct values for the known inputs provided by the 170 test rack.
- 4) Watch_rmdc showed that the 170 returned the correct fuzzymeter lane status and implemented the correct rate.
- 5) When PermitFuzzymeter1 was changed to NO, the 170 stopped fuzzy metering, as intended.
- 6) Fuzzymeter wrote to the event log file as expected.
- 7) Watch_fuzzymeter displayed the correct inputs, internal calculations, and outcomes of fuzzymeter. The metering rates calculated by watch_fuzzymeter

matched those calculated by fuzzymeter and those subsequently returned from the 170.

- 8) When fuzzymeter was disabled, watch_fuzzymeter correctly displayed that fuzzymeter was not enabled.
- 9) When fuzzymeter had insufficient data, watch_fuzzymeter correctly stated this message.
- 10) When fuzzymeter was disabled, rmdc_comm sent out the old data poll as intended (rather than the new data poll).

Table 13 lists the error checking that fuzzymeter performs upon start-up to verify that the inputs to the controller were specified correctly. Further tests were performed to verify that fuzzymeter detected these errors.

Table 13. Equation Error Checks Performed by Fuzzymeter Upon Start-up

EQUATION CHECK PERFORMED	ERROR MESSAGE
The cabinet name must exist in RMDB	"Eqn:Cabinet name not in RMDB – skipped"
The cabinet station/loop name must exist in RMDB	"Station:loop name not found"
The number of samples to calculate the queue inputs and the percentage of HOV bypass must be less than 128 (1 byte size)	"Number of samples for queue or percent HOV adjustment is too large"

170

The following tests were performed to check for the correct operation of the new 170 logic in receiving the new 170 data poll:

- 1) The fuzzy metering rates were implemented on the enabled lanes whether bottleneck was enabled or disabled for the cabinet. Bottleneck and fuzzymeter could simultaneously meter different lanes within the same cabinet.
 - If the fuzzy metering rate was below the minimum rate allowed for that cabinet, the minimum metering rate was used.
 - If the fuzzy metering rate was above the maximum rate allowed for that cabinet, the maximum metering rate was used.

- 2) The bottleneck-metering rate was calculated correctly when the bottleneck adjustment was sent via the new data poll (which also contained the fuzzy metering rates).
 - When the calculated bottleneck-metering rate was above the maximum rate allowed, the maximum rate was implemented.

- When the bottleneck-metering rate was below the minimum rate allowed, the minimum rate was implemented.
 - The bottleneck metering rate calculation was correct when the MultiLaneSplit was set to 0%. The volume adjustment was done correctly.
 - The bottleneck metering rate calculation was correct for both negative and positive storage rates.
- 3) The local metering rate was calculated correctly when the new data poll was used. (Fuzzy metering was enabled on at least one lane, and bottleneck was disabled for the cabinet.)
- When the local mainline occupancy was less than the first local table occupancy, the local metering rate was the maximum allowed rate.
 - When the local mainline occupancy was between the first and second local table occupancies, the local metering rate was interpolated correctly.
 - When the local mainline occupancy was between the second and third local table occupancies, the local metering rate was interpolated correctly.
 - When the local mainline occupancy was between the third and fourth local table occupancies, the local metering rate was interpolated correctly.
 - When the local mainline occupancy was between the fourth and fifth local table occupancies, the local metering rate was interpolated correctly.
 - When the local mainline occupancy was greater than the fifth local table occupancy, the local metering rate was the minimum allowed rate.
- 4) The control between the different ramp metering algorithms worked properly.

- The time-of-day (TOD) rate was implemented correctly when the new data poll was used. (Fuzzy metering was enabled but the ControlSwitch was set to “TOD.”) When the ControlSwitch was set to “TOD,” the 170 did not implement fuzzy metering or bottleneck metering. Instead, it chose the minimum between the local metering rate and TOD rate.
- When the ControlSwitch was set to “Central” and the bottleneck adjustment was sent via the new data poll (fuzzy metering was enabled on one or more lanes), the 170 chose the minimum between the local metering rate and the bottleneck-metering rate. (The bottleneck rate was only applied for the lanes that did not use fuzzy metering.)
- When bottleneck was enabled for the cabinet and fuzzy metering was enabled for a lane within that cabinet, fuzzy metering overrode bottleneck for that lane. (This control hierarchy was necessary because bottleneck rates are cabinet specific, and fuzzy metering rates are lane specific.)
- When the CentralSwitch was set to “Central” and fuzzy metering was enabled, the fuzzy metering rate was implemented regardless of the local metering rate and TOD rates.

CPU Requirements

CPU measurements for the TAPS were aggregated over two hours to compare their relative computational intensity on the VAX (Table 14). Given approximately the same number of cabinets for which to calculate metering rates, fuzzymeter had CPU requirements similar to those of bottleneck. The CPU requirements of fuzzymeter were reasonable in comparison to the other TAPS. The 5-minute CPU usages of these

processes were also examined. The CPU requirements were nearly constant for all processes for the two hours from 9:20 AM to 11:20 AM on March 31, 1999.

Table 14. CPU Requirements of Processes Over a 2-Hour Period

PID	STATE	PRIORITY	NAME	DIOCNT	FAULTS	CPU	TIME
00000217	HIB	4	SMTP_SYMBIONT	2/108	6	499	00:00:00.5
00003A4A	HIB	5	MULTINET_SERVER	57/706	23357	1211	00:00:58.9
00010E6B	CEF	5	EDIT_20_SEC	74/408	140	338	00:03:12.3
0001130C	LEF	7	_NTY4:	100/476	5129	11536	00:01:22.4
0000F90F	LEF	2	EVENT_LOGGER	112/554	486	439	00:00:03.5
00010710	CEF	2	UPI_XMIT	90/406	1447	266	00:00:01.3
00010711	CEF	5	NOAA_MONITOR	100/490	194	374	00:01:47.7
00010716	CEF	1	DUMYDATA	385/758	4	645	00:02:12.9
00010717	CEF	0	STN_AGGR	6671/7003	1	7159	00:02:15.2
0000FB18	CEF	1	INC_DETECT	75/462	2	351	00:00:00.9
0000FB19	CEF	1	BOTTLENECK	1770/2066	11	2218	00:00:14.4
0000FB1A	CEF	1	FUZZYMETEER	1535/1883	4	1948	00:01:07.0
0000EF1B	CEF	0	FMDB_AGGR	16749/171	2	17418	00:06:20.8

0001071C	CEF	0	FMDB_ARCHIVER	10927/118	3164	13065	00:00:25.3
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BUG REPORT

During the process of testing, one bug was found. This bug is the result of an incompatibility between the new file `ntcip.h` and the `watch_fuzzymeter` software. `Ntcip.h` is one of the new files created by a separate project to implement NTCIP standard communications between TMS and the variable message signs (VMS). This file was implemented onto the real-time system in January 1999 (just after The Fuzzy Logic Ramp Metering Algorithm was implemented). The bug resides in a known line of `ntcip.h` that allocates memory. When the object library is compiled with this line of `ntcip.h`, `watch_fuzzymeter` cannot retrieve good data, although `fuzzymeter` works without any problems. As far as we know, no other processes except `watch_fuzzymeter` are affected by the NTCIP bug. When the object library is compiled *without* this particular line of `ntcip.h`, `watch_fuzzymeter` works without any problem.

To get around this bug for the time being, `watch_fuzzymeter` links to a different object library, which is identical to the object library used by all other processes except that the one problematic line in `ntcip.h` is deleted. Although this version works fine for a short-term solution, it is highly recommended that the NTCIP bug is fixed as soon as possible. Fixing bugs in the NTCIP project is outside the scope of this project. Memory problems such as these are the most dangerous type of bug. Although the consequences appear benign for the present time, as the databases grow over time, locations for process memory may move around. In the future, the NTCIP bug could overwrite different parts of memory and damage more critical operations. Furthermore, if changes are made to the object library before the NTCIP bug is fixed, be sure to update the same changes in `watch_fuzzymeter`'s object library for proper configuration. The known details of this

bug have been reported to the TMS software manager at WSDOT, who is working on the problem.

PERFORMANCE EVALUATION SOFTWARE

One of the difficulties of on-line testing was that the system-wide performance measures that we desired were not readily available. Ideally, we wanted to know the total distance traveled by all vehicles in the system, the total travel times of all vehicles in the system, and ramp queue delay. Realistically, the scope of this project was limited to performance measures that we could estimate through a combination of hardware and software processing. In addition to mainline performance measures, we needed queue performance measures to determine if there was system-wide benefit. (For further details on which performance measures were used and why they were chosen, see the evaluation report, Taylor and Meldrum, 2000). We evaluated several methods of obtaining and processing data, and we chose the one best suited to our needs.

METHODS EXPLORED

We evaluated several possibilities for gathering 5-minute data and performance measures for our study sites, and we decided which of these would best suit our needs to analyze the performance of the new ramp-metering algorithm:

- 1) Trafficview — This was a sidewalk.com Web page that used WSDOT's 20-second data to make travel time estimates. The estimates were based on current (not predicted) conditions. Trafficview emailed travel times from the study sites as frequently as we wanted. Although this was a very user-friendly tool, the difficulty was in the availability and reproducibility of this performance measure. We did not know if TrafficView would be in operation when we needed it. (In fact, it was not, so it is

fortunate that we did not choose it.) We also did not know the exact methods used to calculate the travel times. And we did not know if we could apply the same method in subsequent studies as a standard of comparison. Despite the convenience, we chose not to use it for these reasons.

2) CDR — This software retrieved archived 5-minute data, which was automatically sent from the central VAX to another server every night. From this data server, the 5-minute archived data could easily be retrieved from anywhere on the network. We found that CDR was very useful. Using CDR, we created data files of requested data that we could import directly into Excel. Using CDR data, we created throughput histograms of our study sites in Excel. (See test results in evaluation report, Taylor and Meldrum, 2000). We also used CDR to estimate the control parameters at previously unmetered ramps. (See system-wide implementation of the evaluation report.) Primarily, we used CDR to preprocess the data for CD Analyst.

3) CD Analyst — We decided to use the CD Analyst software produced by the FLOW project (Ishimaru and Hallenbeck, 1999) because it will be the standard performance evaluation software for our region and because it provides a uniform method for future comparisons. We used FLOW software to produce occupancy contour maps of the study sites, frequency of breakdown plots, and travel time measures. The occupancy contour maps were very useful in evaluating congestion on the mainline. (See test results in evaluation report, Taylor and Meldrum, 2000). The frequency of breakdown plots was very valuable for determining which stations to use as downstream inputs for a given ramp. (See downstream input section of the training manual, Taylor and Meldrum, 2000). We found that the travel times were not accurate enough to be of

use because of the way in which the speed was estimated and the fact that ramp delay was not included. (See discussion of performance measures in the evaluation report).

GETTING 20-SECOND DATA

While CDR and CD Analyst software are suitable for mainline performance measures, they do not provide measures of ramp metering queue performance. To evaluate ramp queues, ramp delays, and metering sensitivity to mainline conditions, analysis of the queue was necessary. In particular, we thought it was necessary to use 20-second data because previous attempts by Ishimaru and Hallenbeck found that the 5-minute data were not adequate for queue analysis, and it was believed that 20-second analysis would be accurate enough for queue analysis. For this reason, we continued to explore ways to retrieve and analyze 20-second data for queue analysis to be used in conjunction with the mainline performance measures:

1) TDAD — This project was a 20-second database project at the University of Washington that archived 20-second data and provided files of queried data. Unfortunately, we found that 9 months of data had been lost, and the database was not available to us for use. There were some difficulties accessing the data behind firewalls, and we had no way of storing the results of our query into a file because of the way that the Java language handles security. For these reasons, we could not use TDAD.

2) SDD — This was a UW project that provided 20-second data to clients in realtime. We installed the software to retrieve these data. Although this server worked, much more programming would have been necessary to parse and process the incoming data into a usable form.

3) VDR — This was a TMS utility that created 5-minute data files directly from the VAX as specified by the user. We explored the possibility of modifying this utility to

create 20-second data files as well. It turned out that the modifications necessary for VDR to create 20-second data files would be too involved for this project.

4) `Get_20_sec_data` utility on VAX — This was a VAX utility that produced 20-second data files for the times and loop detectors specified in an input file. However, the companion software to convert the resulting data files to ASCII on the PC had been lost by WSDOT years ago. We looked at the code and discovered that it was easy to modify the code to write ASCII files (see `edit_20_sec.c` section under NEW CODE). In comparison to the other methods of gathering and processing 20-sec data, this one was the easiest of the four methods discussed here, so we decided to use it. We made the necessary changes to create ASCII files, wrote a makefile to compile the software in a bubble environment, and installed the code on the VAX. Most significantly, we wrote code that automates the process of gathering 20-sec data. Formerly, it was necessary to modify the input file every day with the proper collection date, times, and stations. The new code that we wrote, `edit_20_sec`, checks the date and time so that it automatically collects the desired loops and stations for morning metering between 6 am and 9:30 am on weekdays. For the afternoon metering period, it collects the desired loops and stations between 2:30 and 6 p.m. on weekdays. This new software ran continuously for the several months during which we evaluated our study sites, and these 20-second data files were successfully used to evaluation the queue with respect to ramp metering performance.

PROCESSING 20-SECOND DATA

We wrote software to analyze 20-second data for evaluating ramp-metering performance. The software that processes 20-second data and provides performance measures must run on Matlab. While we wrote this code for our purposes of evaluating

ramp metering performance, other researchers and TSMC personnel expressed an interest in this type of software tool. For this reason, we have written the code in a modular manner that is easy to modify, and we have made the code available to anyone at WSDOT who needs it. (Look on the TSMC directory of the Quartz server for the 20_sec_analysis directory at the Northwest District).

The files ending in '.m' are run from the Matlab command window by typing the file name. The files are either script files or functions. Script files read the data and run the commands in the m-file using the variables in the workspace. Functions require certain inputs. You can get help on the command line for any of these files by typing *help filename*. All files can be run stand-alone or run from the main program, **queue**, which is menu driven. To run these functions stand alone, you must have any necessary variables in the workspace. You can get the variables into the workspace either by parsing a file using **queue** or by loading variables from a file of type *.mat. To see the defined variables, type *who*. To see the value of any variable, type the variable name. If you want to save the variables in your workspace at any time (to save you from reparsing the original data file), type *save ES-xxxx.mat*. When you want to restore the data, type *load ES-xxxx.mat*.

The capabilities of the new software are summarized, followed by the module names related to those functions.

- 1) Open an ASCII file that was created by the VAX utility **get_20_sec** and parse the 20-second data file to get the volumes, occupancies, and data validity flags for entering and exiting ramp data: **cab_sort.m**, **cablistinput.m**, **queue.m**, **parse_data_file.m**, **queue_params.m**, **parse_main.m**, and **main_params.m**.

- 2) Patch bad data using good adjacent data, if possible, and create a bar graph of data quality: **data_patch*.m** and **data_quality.m**.
- 3) Simulate ramp metering for each 20-second cycle: **queue.m**, **get_mr**, **meter_params.m**, **local_meter.m**, **interpolate.m**, **local_params.m**, **queue_override_occ.m**, and **queue_override_vol**.
- 4) Estimate and plot the storage rates for each 20-second cycle (using either real passage volume or simulated metering rates): **queue.m** and **calc_queue*.m**.
- 5) Estimate and plot the ramp queue in vehicles as the accumulative sum of the storage rate on the ramp: **queue.m** and **calc_queue*.m**.
- 6) Plot the ramp demand and the ramp passage versus time for general purpose lanes, HOV lanes, or the sum of general purpose and HOV lanes: **queue.m** and **calc_queue*.m**.
- 7) Calculate and plot the queue performance measures: **plot_queue_occ*lane.m**
- 8) Tune and graph the fuzzy classes to determine the appropriate design: **trap*.m** and **default_tuned*.m**.

Pseudo code is given for some of these files.

Cab_sort.m — Reads the aggregate data files and creates the new data files for each cabinet. Although it is not necessary to run the **cab_sort.m** preprocessor, it will speed up the queue analysis if you're examining multiple on-ramps. This process may take a while. If you have a big input file, you may want to run this over night.

- Opens the ASCII file created by the VAX utility **get_20_sec**.

- Opens and reads the file, **cablistinput.m**. **Cablistinput.m** must contain a list of cabinets for which data files will be created by **cab_sort.m**. Modify this file to include the cabinets that you want! This file must use the specified format:

```
cab_list = {'ES-xxxx' 'ES-xxxx',...};
```

- Sorts file by cabinet name.
- Creates a new 20-second data file for each specified cabinet name.

Queue.m — the main menu driven interface. Be sure to review the loop names in **queue_params.m** before running **queue.m**! Be sure to review and if necessary, update the equations in **calc_queue*.m**!

- Opens the ASCII file created by the VAX utility `get_20_sec`.
- If the user chooses to parse a data file (as opposed to loading the variables into the workspace from a *.mat file), **parse_data_file** is called.

Parses data file to get the volumes, occupancies, and data validity flags for entering and exiting ramp data

- If the user chooses to patch any bad data, the appropriate **data_patch*.m** is called.

Estimates bad data using good adjacent data if possible.

Creates bar graph of data quality with percentage of good+fixed.

- If the user chooses to ramp meter the data, **get_mr** simulates ramp metering for each 20-sec cycle. (You would want to use this feature on unmetered data for ramps that have not previously been metered in order to estimate the queue.

Get_mr actually writes the metering rate into the passage rate, so do not use this function if you want to analyze the queue performance of metered data.)

- If the user chooses to calculate the queue, the appropriate **calc_queue*.m** is called.

Estimates the storage rate for each 20-second cycle.

Estimates the queue length in vehicles as an accumulative sum of the storage rate.

Estimates the queue delay using the current metering rate .

Plots queue length and queue delay during metering.

Queue_params.m is an m-file used by **queue.m** to specify the loop names, cabinet name, and directory name. Review this file and update it before running **queue.m**. Enter the cabinet name for the ramp queue analysis. If you do not run the preprocessor called **cab_sort**, you'll need to rename your data file to match the cabinet name to be analyzed with the form "ES-xxxx.log." If you need the mainline local station and it has a *different* cabinet name than the ramp loops, then you must use the original data file. (The **cab_sort** preprocessor won't work for you.) Revise loop names as needed. Do not delete the ones you do not need, but make sure that the ones you do need are correct! If you want to analyze lane 3 and it is not adjacent to lanes 1 and 2, set `gp1_passage` to `'_MS_P_3'`, and set `gp1_demand` to `'_MS_Q_3'`. Do likewise for the HOV passage and demand. You must rerun **queue.m** for each set of adjacent ramps. In other words, run **queue.m** first for the adjacent metered lanes 1 and 2. Then run **queue.m** again for independently metered lane 3. If lane 2 is not adjacent to lane 1, the analysis for lanes 1 and 2 must be done independently. The code does not currently support lane 3 if it is metered adjacent to lanes 1 and 2. Be sure to look at actual loop

locations to determine whether to use the queue loops, intermediate queue loops, or advance queue loops for the best representation of the demand. (In other words, which queue loop is adjacent to the HOV demand? Which queue loop encompasses the end of the queue? Do you have the unusual case where the queue loop includes the HOV volumes before it splits off, as in geometry case #5 of the **queue.m** menu?) Be sure to examine the equations in **calc_queue*.m** to see if these are used appropriately. If an error occurs during **calc_queue*.m**, you have probably not specified your loop names correctly. Compare them to the actual loops in the data file. You also may have specified the wrong geometry.

Parse_data_file.m — Parses the raw data file to extract the desired data. **Queue_param.m** defines what cabinet/loop/stations names to extract.

Data_patch*.m — Patches any bad data and graphs them. These modules call the function **data_quality.m** to estimate the bad data by interpolating with good data that are adjacent in time. Bar graphs show old good data plus new good data quality. They are called by **queue.m** or can run standalone with the variables in workspace. If a module is run more than once on the same raw data, it will patch the patched data. (It may continue to increase the number of interpolated data points, but the reliability of repatched data decreases with each run of data patch.) Run only one of the following modules, depending on your ramp metering geometry. These module names correspond to how many lanes are metered side-by-side where crossover can occur, not necessarily to the lane numbers:

- 1) **Data_patch_1lane.m**

- 2) **Data_patch_1lane_hov.m**
- 3) **Data_patch_2lanes.m**
- 4) **Data_patch_2lanes_hov.m**
- 5) **Data_patch_1lane_hov_inc.m**

Data_quality.m — Function called from **data_patch*.m** to patch bad data. It returns the percentage of good data samples, the percentage of fixed data samples, and loop structure with fixed data. It tries to interpolate the bad data with timewise adjacent data.

Get_mr — a function called from **queue.m** that returns the metering rate. It uses the function protocol: `passage = get_mr (main_data, queue_data, adv_queue_data, hov_flag, hov_data, lane_no, time_index)`. **Get_mr** calls **meter_params.m**, **local_meter.m**, and **queue_override.m**. It calculates metering rates for all time intervals given the mainline occupancy, queue occupancy, advance queue occupancy, an HOV flag to tell if there is a bypass, the HOV bypass volume, the lane number to meter, and the number of intervals. **Get_mr** must be called once for each metered lane. The results are stored in the passage loop variable, overwriting the real passage loop volume (unless you call it with a different variable name for the result).

- **Meter_params.m** — a script file that contains the parameters used in the Local Metering Algorithm. Be sure to update these parameters before running **get_mr.m**! This file is called by **local_meter.m** and by **queue_override.m**. Rows (separated by colons) correspond to the lanes 1, 2, and 3. `Queue_occ` contains the queue occupancies at which to start and end the queue override for

each lane. Queue_timer and adv_q_timer contain the duration in minutes that the occupancy exceeds the start queue occupancy before adding the queue_adjust 1 and queue_adjust 2 to the metering rate. Queue adjustment, queue override, table_rate, max_rate, and min_rate are all in vehicles/minute.

- **Local_meter** — a function that returns a local metering rate given a mainline occupancy and the metered lane number. It is called from **get_mr.m**. It calls **local_params.m** and **interpolate.m**. Be sure that **meter_params.m** contains the correct parameters.
- **Queue_override** — Given the queue occupancy, advance queue occupancy, the lane number to meter, and the previous override state, this function determines the new override state and calculates metering adjustment. It is called from **get_mr** and calls **meter_params.m**.

Calc_queue*.m — Calculates the storage rate and the total vehicles in the queue for each 20-second cycle. It plots the storage rate and the vehicles in the queue for each lane versus time. It also plots the total storage rate and the queue for the metered lane(s), taking into account any weaving in and out of the HOV bypass lane. *Update these equations as they apply to each ramp! Check the queue_params.m input file to review the loop names!* If you have run a metering simulator, the passage volume will be the calculated metering rates rather than the actual passage volume. If you want to save your data for this cabinet without reparsing, type "save ES-xxxx.mat". When you want to restore the data, type "load ES-xxxx.mat". Then type calc_queue*.m to replot. Run only one of these modules, depending on your ramp geometry. The following module names

correspond to how many lanes are metered side-by-side where crossover can occur, not necessarily to the lane numbers:

- 1) **Calc_queue_1lane.m**
- 2) **Calc_queue_1lane_hov.m**
- 3) **Calc_queue_2lanes.m**
- 4) **Calc_queue_2lanes_hov.m**
- 5) **Calc_queue_1lane_hov_inc.m**

TRANSFERABILITY

Even before publication of the test results, we received many requests regarding the applicability of this algorithm to other regions. This code is customized for WSDOT's system – it is not “plug and play” for new systems. Successful implementation requires knowledge of the site specifics, with controller inputs determined as described in the training manual (Taylor and Meldrum, 2000). *The concepts behind this algorithm are certainly transferable, but the algorithm may need modification depending on detector types, detector placement, sampling frequency, and control objectives.* The fuzzy classes must be determined with respect to the detector data characteristics and control objectives. The control objectives are embedded into the rule base. For WSDOT's system, balancing the queue rules with the mainline objectives is a necessary feature. For regions that do not have such oversaturation, their control objectives may be different. Regions that will see the most benefit from this type of logic are those that have ramp queue detection, the need to balance mainline objectives with queue objectives, and oversaturation both on the mainline and ramps. The more congested the facility, the greater the effect of an event. Incidents occur with greater frequency and bigger consequences on highly congested facilities. For this reason, adept incident handling is a key feature of the Fuzzy Logic Ramp Metering Algorithm for Seattle. Likewise, other regions with oversaturation will value the ability of this algorithm to handle a wide variety of conditions.

Although the controller code itself is relatively simple, the interface between the system software, control algorithm, field devices, and user interface may need considerable customizing. For instance, this implementation involved modifying 77,000

lines of C code for the interface to WSDOT's highly customized TMSC VAX system (not including the TMS PC software), compared to 8000 lines of new C code (not including the performance evaluation software). Of those lines of new code, only 8 percent of the new lines are for the controller code itself. (The others are for the interface as well.) The fuzzy logic controller itself consists of the following modules: **calc_fuzzy_rate**, **fuzzify**, **rules**, and **defuzzify**. (For those interested in purchasing a non-exclusive license for new source code created in this project, contact Deirdre Meldrum at the Electrical Engineering Department of the University of Washington. The University of Washington owns the code, and WSDOT owns a non-exclusive license to the code.)

RECOMMENDATIONS

Because this project involved implementing the Fuzzy Logic Ramp Metering Algorithm system-wide, we also fully trained the freeway operations engineers on how to use this system. After understanding how `watch_fuzzymeter` works, the freeway operations group requested that the TMS operator console display similar data. Implementing this request is not as simple as it may appear. Fuzzymeter does not store all of the internal calculations displayed by `watch_fuzzymeter`. `Watch_fuzzymeter` only stores the internal calculations for the chosen ramp. If the operators wanted to access these data, it would be necessary to modify the TSMC VAX software to store them in a global database. Rather than clutter up the RMDB with these data, it would be better to store the data in new fuzzy database. However, the operators do not need this information within the TMS PC software because they can easily access it through vt320 (a VAX terminal emulator), which has been installed on all of the operator PCs. They have been instructed on how to access `watch_fuzzymeter` through vt320. It is recommended that the operators become more comfortable logging directly on to the VAX through vt320 to access this information, because modifying TSMC VAX software to send these data to the TMS PC software is not cost effective for the marginal convenience it would provide.

We recommend the integration procedure that we used in this project. By doing preliminary testing on a spare microVAX that duplicated the real environment, we were able to thoroughly test the code functionality without impacting operations. The bubble environment (described in the integration procedure) was a useful intermediate step between off-line testing and fully integrated on-line testing. With this approach, we were

able to avoid any downtime or bugs caused by the on-line implementation of the Fuzzy Logic Ramp Metering Algorithm.

The time and funds required for software development are typically greatly underestimated. For this project, over 90 percent of the budget was spent on software, while only 10 percent of the budget was needed for design, hardware, implementation, and evaluation. Considering this statistic, many projects may benefit by hiring experienced programmers. Despite the high cost of experienced programmers, they should be able to get the job done faster, saving money on the overall project. The software interface and integration were particularly time-consuming. Of the 85,000 lines of new or modified C code for this implementation, less than 1% of those were for the controller code itself. When dealing with software integration and testing, particularly for a complex system that does not permit downtime, allow ample funds to develop, test, integrate, and evaluate software in a quality manner. For instance, the Bottleneck Algorithm never worked properly for years after its implementation and was only recently deployed successfully when its 170 code was debugged through this project. Likewise, we strongly recommend that WSDOT fixes the NTCIP bug from the VMS project, or consequences could be severe (see Bug Report). With high turnover rates in employees, documentation is important for the long-term success of software applications (see Lessons Learned in Piotrowicz and J. Robinson, 1995). In a nutshell, be sure that budgets for implementation projects include ample funds for adequate software testing and documentation as part of the contract.

For successful deployment, the importance of communication cannot be overrated. This implementation required extensive coordination among programmers, system administrators, freeway operations engineers, software maintenance persons, and

other researchers. When communication between software engineers did not take place on a daily basis, there were problems with shared resources, incompatible integration schedules for different projects, and software configuration issues. With frequent feedback from the freeway operations and software engineers, the quality of the design was improved. Testing had to be scheduled carefully to avoid affecting other projects and events. Software status needed to be communicated to hardware personnel to prevent incompatibilities with field devices. Correspondence with commuters at the study sites allowed us to fine-tune the metering performance. Progress and results needed to be communicated to managers to build support for the project. Although it may seem excessive to send out daily or weekly emails regarding the project status, schedule, and anticipated needs, this was found to be necessary to coordinate activities among all individuals who were affected or who could affect the project.

At the onset of this project, there was a lack of software support that made this implementation more time-consuming. WSDOT is now heading in the right direction regarding software infrastructure. It now has a knowledgeable system administrator for the TSMC VAX. It has greater in-house knowledge of how to make modifications to the TSMC VAX code, PC code, and 170 microprocessors. In-house knowledge is very helpful when fixing bugs, making improvements, or expanding the system. WSDOT has improved its file maintenance, including backups, security, makefiles, and code management software. WSDOT should continue to invest in continuous improvements to the software infrastructure and software personnel. The benefits of proper software infrastructure include improved operations and better risk management.

As databases grow, features are added, and data requests increase, the demand increases on the central computer's processor speed, communication speed, and memory

requirements. It is possible that at some point in the next couple years, an engineer planning to add a demand on the VAX may discover that the VAX cannot support the planned functionality. The VAX computer was obsolete from the day implementation was finished. Because of this obsolescence, maintaining the VAX has been expensive. Because migrating the TSMC VAX software to a new platform may require several years (remember how many years it took to migrate to the VAX), we recommend that WSDOT begin the planning stages for this event. The recommended study should include an estimate of how long the VAX will be able to handle projected demands, the optimal software and hardware architecture for the next system, and the recommended timeline for migration to the new system. Factors that should be considered in determining the new system include how to handle loads, hardware failures, test beds (such as multiple processors to share loads, take over in case one fails or is devoted to testing), operating system, memory requirements, processor speed, modularity, expandability, connectivity, data I/O speed and ports, data archiving, automatic backups, automatic performance measures, standardization, and security. The study should also estimate the cost of implementing and maintaining the recommended system, as well as a time line for the migration. With foresight and planning, WSDOT will confidently meet growing requirements.

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The contributions of many individuals at WSDOT were integral to the success of this project. Mark Morse assisted with software design and testing, as well as modifying the 170 logic. Paul Neel provided input on software design. Brian Dobbins tested the 170 microprocessors. Greg Leege and Don Vondran installed and field-tested the 170 microprocessors. Lanping Xu configured and maintained temperamental VAX machines. Harriette Lilly contributed to the software integration procedure, software configuration, and VAX software debugging. Michael Kastner and Michael Forbis debugged the TMS PC software. Without this cohesive team of talented and knowledgeable individuals, this project would not have been possible.

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