EVIPAS: A Computer Model for the Optimal Design of a Vehicle-Actuated Traffic Signal

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The EVIPAS model described is a computer program designed to analyze and optimize a wide range of intersection, phasing, and controller characteristics of an isolated fully actuated traffic signal. It will evaluate almost any phasing combination available in a 2- to 8-phase NEMA type controller and similar phasing structures for a Type 170 controller. The model will provide optimum timing settings for pretimed, semi-actuated, fully actuated, or volume-density control using a variety of measures of effectiveness chosen by the user. A wide range of geometric features, phasing alternatives, and detector layouts can be evaluated. EVIPAS combines a user friendly input module with a multivariate gradient search optimization module and an event-based intersection microsimulation. It has been field-tested and validated and replicates well-observed vehicle and signal behavior. The model is programmed in Fortran 77 and currently can run on VAX 8600 and IBM 3080 mainframes.

In recent years traffic signal design has been facilitated by the increasing availability of computer software for signal timing analysis. Most of the models available, however, are calibrated for pretimed signals. The *1985 Highway Capacity Manual (1)* provides a set of capacity analysis procedures for signalized intersections that are heavily dependent on a signal timing and phasing plan. Further, a large number of the new signals being installed in North America are fully vehicle actuated with many of these using volume-density control. Therefore, a clear need exists for software that will provide optimal design for vehicle-actuated traffic signals.

The software that is currently available has only limited applicability. The only single intersection model *(2)* that optimizes design parameters is SOAP84. This model depends heavily on the approach of Webster *(3)*, which is mainly for pretimed signals. Although SOAP84 does provide some assistance for dealing with vehicle actuation, it does not attempt to provide a complete analysis capability for the many options that are available.

The TEXAS model *(4)* is not widely circulated. It is a microsimulation of an intersection with vehicle-actuated signals, but provides no direct optimization capability. The model is rather slow, and it is not clear how well it deals with all of the individual timing parameters for fully actuated volume density control.

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NETSIM is a network traffic microsimulation that has a detailed vehicle-actuated signal capability for individual intersections *(5)*. This model has no direct optimization capability and is also slow. It is primarily intended for the analysis of area control type problems.

The EVIPAS model described in this paper is able to analyze and optimize a wide range of intersection geometric configurations, phasing, and controller characteristics of a fully vehicle-actuated isolated traffic signal. It will evaluate almost any phasing combination available in a one- or two-ring NEMA type controller and similar phasing structures for a Type 170 controller. It will provide the optimum timing settings for pretimed, semi-actuated, fully actuated, or volume-density control by using a variety of measures of effectiveness chosen by the user. These include delay, fuel consumption, other operating costs, and emissions. A wide range of geometric features, phasing alternatives, and detector layouts can also be evaluated.

The EVIPAS model has a user friendly input module and is currently programmed for the VAX 8600 and IBM 3090 mainframes.

BACKGROUND

VIPAS was a model originally developed at the Pennsylvania Department of Transportation (PennDOT) in Harrisburg, Pennsylvania by Tom Bryer and programmed by John Breon *(6)*. The department realized the need for a model to optimize actuated signal design and also provide an estimation of the economic benefits of installing actuated traffic signals.

The major component of VIPAS was a microsimulation of a signalized intersection. The simulation was a second-by-second vehicle scanning procedure using the car-following algorithms of the Federal Highway Administration INTRAS freeway simulation *(7)*. For vehicle queues and queue discharge from the stop line, more efficient flow discharge models substituted for the individual vehicle scanning process.

An unusual characteristic of the model was the randomly generated vehicle arrivals for multilane approaches. It has been well established that the total arrival pattern of a multilane approach is not just the simple sum of the random distributions on the individual approaches due to the correlation between vehicles across lanes. To overcome this problem VIPAS used specific multilane arrival distributions calibrated from test runs by FHWA on the INTRAS simulation. These distributions were stored in VIPAS as the inverse distribution functions in the form of nth degree polynomials.

Other features of the initial VIPAS model included four vehicle types, including car, bus, truck, and semi-trailer, with acceleration rates particular to each vehicle type. The acceleration for each vehicle type had two ranges with a higher acceleration below a given threshold speed. Similarly, for deceleration, all vehicles coast at a low deceleration between their desired speed and a deceleration threshold of 0.9 times the desired speed. Below this threshold a greater deceleration is imposed. The desired speeds for the vehicles are generated randomly by the normal distribution.

Various measures of effectiveness were available to the user. These include total vehicle delay, stopped delay, person delay, fuel consumption, total operating costs, and vehicle emissions.

The VIPAS model was implemented on the department's IBM 3081 computer. Operational use of the model revealed a number of difficulties including the following:

1. It dealt only with a restricted set of geometric and phasing configurations.
2. It allowed only one detector per approach lane.
3. The model required further field verification.
4. There was a desire to make it more user friendly.
5. The total was very large and rather slow, which inhibited its use by field engineering staff in the department.

To enhance the capabilities of the VIPAS model and correct any deficiencies, the University of Pittsburgh was awarded a research project by the PennDOT Office of Research in 1985. The objectives of this project were to expand and generalize the capabilities of VIPAS, carry out field studies for calibration and validation, provide a user friendly input structure, and make the overall model smaller and faster.

THE NEW MODEL

An analysis of the structure of the VIPAS model indicated that the simulation could not be easily generalized to cover the required broad range of traffic and signal conditions, and the optimization methodology was not suitable for full multivariate situations. Consequently, a new optimization algorithm and a new intersection simulation were designed and programmed. The original VIPAS traffic characteristics and vehicle generation routines were combined with these new models to give the enhanced version EVIPAS.

The new EVIPAS model consists of five major modules:

1. An input module that provides a user friendly interface for the user: INPROC,
2. A generation module that generates all vehicle and pedestrian arrivals and their characteristics: GENRAT,
3. An optimization module that finds the optimum settings of the selected timing variables: OPTSIM,
4. An intersection simulation that provides the function calls for the optimization: PROCES, and
5. An output module: OUTPUT.

Input Processing: INPROC

The purposes of the input processing routines are to

1. Provide a user friendly environment whereby appropriate data files can be created, updated, and edited using an interactive or batch mode; and
2. Process or transform user data into error free, compiled data for use in the VIPAS simulation and optimization processes.

INPROC, which is designed to be used independently, helps users to create new data files, update existing files, and edit appropriate data elements by using an interactive or batch mode. Each data file is used for a specific project. INPROC then creates internally two compiled files that will be read by GENRAT and PROCES. This ensures that the optimization and simulation runs are on error-free data.

VIPAS requires three data sets per data file: (a) intersection characteristics, (b) signalization characteristics, and (c) traffic characteristics.

INPROC will guide users through all three data sets from data element to data element in logical sequence or at the users' option to edit, review data, or seek help. Given a strict and inflexible FORTRAN 77 programming environment, this liberal input philosophy is made possible by a format-free, input interface routine (FREFRM) whereby all users' input is received and assessed for its validity in terms of the data elements requested. Valid inputs are those within predetermined upper and lower bounds. This strategy is used to filter out outliers and unqualified inputs. A default value is assigned with the user's approval when an invalid input is encountered. FREFRM provides the primary mechanism to filter inputs and to achieve some degree of user friendliness while still operating in the FORTRAN 77 programming environment. FREFRM adopts suggestions by Wright *(8)* in terms of man-machine interfacing in the FORTRAN environment.

For intersection characteristics, users are requested to provide information pertaining to the physical features of the study intersection, including (a) number of approaches (maximum of 5); (b) number of lanes in each approach (maximum of 5); (c) detector locations (combinations of presence or passage detectors, or both, with up to three per lane); and (d) saturation flows adjusted only for width and gradient factors according to the *1985 Highway Capacity Manual (1)*. For a particular case study, the intersection characteristics may be kept constant or varied to test alternative physical configurations. EVIPAS, however, simulates and optimizes for a given set of intersection characteristics.

EVIPAS is designed to simulate and optimize fully actuated, semi-actuated, volume-density, and pretimed signalization with or without pedestrian actuation. For simulation purposes, users are required to provide various timing parameter values for each phase defined. For an actuated signal this would include the initial intervals, the unit extensions, the maximum intervals, and the yellow and all-red clearance intervals. For optimization purposes, users are not required to provide the timing for those parameters they are choosing to optimize. VIPAS will create its own timing parameters as a starting point before determining the optimum values. Users may provide upper or lower bounds, or both, for the variables being optimized.

The bulk of the data input requirement is in the definition of the traffic characteristics. INPROC can handle a week's data that has been segmented or separated into periods of similar traffic characteristics, such as morning peak-hours during weekday, and weekend traffic. For each period, users are to provide parameters that will typically describe the traffic characteristics during that period including (a) volume per lane, (b) traffic composition, (c) traffic turning movements, (d) average speeds, and (e) pedestrian counts. Periods may be linked together and can be assigned different weighting factors.

The final stage of INPROC is to check and compile user inputs into error-free data. A special routine, COMPILE, checks for errors and inconsistencies in user data hierarchically from intersection level to approach level and from approach level to lane level. In addition, data elements are checked for errors and inconsistencies at the same level. If any data element is found in error, the user is prompted by COMPILE to make the appropriate correction.

Vehicular and Pedestrian Generation: GENRAT

The purpose of GENRAT is to generate stochastically the traffic and pedestrian arrivals as defined by the traffic characteristics in INPROC for each period of study. Vehicles are generated randomly at the source of each approach, which is a predefined point upstream of the intersection stop line where traffic flow is not influenced by the intersection. Pedestrian arrivals are randomly generated at the push-button. Vehicle and driver characteristics, which include (a) arrival time, (b) vehicle type, (c) driver type, (d) source lane, (e) turning direction, (f) speed, and (g) follower, are assigned randomly to each vehicle generated.

For headways for low traffic volumes of less than 40,100 and 200 vph for one-, two-, and three-lane approaches, a negative exponential distribution is assumed. For one-lane approaches with higher volumes, Kell's composite exponential distribution is used *(9)*. For multilane approaches with higher volumes, the probability distribution function calibrated from INTRAS is used. Special care is taken to ensure logical sequence and proportionality of arrivals per lane at the source, especially in multilane approaches.

Other vehicle characteristics such as vehicle type, driver type, source lane, and turning direction are generated by discrete uniform distributions, whereas vehicle speeds use the normal distribution and pedestrian arrivals use the negative exponential distribution.

The output of GENRAT is a set of vehicles stored in a data file, with assigned characteristics for each approach during the period of study. Users have the option of checking the statistics of the GENRAT output by using the GENSTAT routine, which is a support module that computes statistics for the arrival data generated by the GENRAT module. For each lane and period, GENSTAT computes the mean and standard deviation of headways; median headway; minimum and maximum headway; the order statistics for the quantiles 1, 5, 10, 25, 75, 90, 95, and 99 percent; mean and standard deviation of the vehicle speed; vehicle-type frequency distribution; turn-direction frequency distribution; and driver-type frequency distribution.

Optimization: OPTSIM

As with most current traffic models, such as TRANSYT *(10)*, the optimization in the original VIPAS was a sequential univariate procedure. The problem with using these types of methods is the time needed to converge and the fact that the method does not guarantee a local optimum.

The optimization module in the EVIPAS is a multivariate procedure that uses quasi-Newton methods to find the optimal values of the parameters. Numerical procedures compute first and second derivatives of the function for a given vector of parameter values. The values of these derivatives are used to determine the direction and size of steps from one parameter vector to the next and to determine whether the minimum is reached. The algorithms are designed to avoid certain types of local minima, although there exist conditions for which these methods fail to find the optimum solution. In general, however, these methods are among the best available for the solution of this class of problems.

The function for the optimization is the measure of effectiveness (MOE) output of the intersection simulation. To make a function out of a simulation model, three computational problems must be addressed. First, the model must be structured so that a run of the simulation model is functionally dependent only on the values of the vector of input parameters. All other data necessary for the operation of the model must be fixed for all iterations of an optimization run. Second, at the start of each iteration, the model data and starting conditions must be identical. Thus the model must be reinitialized to the same status at the beginning of each iteration. Third,, the computation of the output value must not change from iteration to iteration. Meeting these requirements is an important feature of the EVIPAS structure.

From the perspective of the optimization module, a function is a function. It matters not whether the function has a simple analytic form or is a large simulation model. The optimization module is only concerned with the relation of the parameter vector and the associated output value. The optimization algorithms and numerical methods used in EVIPAS are on pseudocode programs and subroutines reported by Dennis and Schnabel *(11)*.

In implementing this general optimization algorithm, several important choices must be made. The first is the determination of the size of the linear step to ensure that an improvement in the function will occur. If no improvement is found, the algorithm backtracks to determine a better one by fitting a cubic to the last few values and solving the cubic for its minimum.

The second choice concerns how to compute the Hessian matrix, which can be done by finite-difference approximations or secant update methods. The finite-difference approximations require that the function be evaluated many times, whereas the secant update approach does not require that the function be evaluated; instead it solves a set of linear equations using the old Hessian method and the current values of the gradient and parameter vector. Because function evaluations are computationally expensive in this application, the preferred method is the secant update approach as it minimizes the number of times the simulation model must be run.

Nevertheless, for large problems, many function evaluations are required, perhaps approaching several hundred. Fortunately, most signal problems involve a relatively small number of variables and the optimization converges rapidly.

Intersection Simulation: PROCES

The simulation of an intersection under vehicle-actuated control presents a set of traffic movement alternatives that are so complex as to require a microsimulation. However, most microsimulations require considerable computer time—a major disadvantage for a model such as EVIPAS, which requires many function calls in its optimization.

The simulation that has been developed for the EVIPAS has several structural features that are designed to enhance its efficiency. Primarily it is an event-based individual vehicle simulation, with the events being green extensions or green termination. The simulation constructs vehicle trajectories in space-time according to a linear car-following model, which is related to the model used in the INTRAS freeway simulation. The car-following algorithm has been reformulated, however, to provide a more realistic handling of driver reaction times. Each trajectory consists of a series of nodes that represent changes in acceleration. The linear car-following model is

$$a(n) = b[v(n) - v(n-1)] \quad (1)$$

where

$a(n)$ = acceleration of the nth vehicle at time $t + T$,
$v(n)$ = speed of the nth vehicle at time t,
$v(n-1)$ = speed of the $(n-1)$th vehicle at time t,
T = driver reaction time, and
b = a coefficient.

This formulation leads to a headway condition

$$x(n) = x(n-1) + M + kv(n) \quad (2)$$

where

$x(n)$ = distance coordinate of vehicle n at time t,
$x(n-1)$ = distance coordinate of vehicle $n-1$ at time t,
M = minimum stopped distance headway between the vehicles, and
k = driver reaction time = $T = 1/\alpha$.

This is the basic car-following model that is used in INTRAS but with time-homogeneous processing at 1-sec intervals. Many calculations are needed to form a following trajectory. Although the reaction time T is in the car-following formula, it is not represented well in the simulation.

In EVIPAS, car following is achieved by first setting a target position for the follower in relation to the change of acceleration of the leader and Equation 2. The trajectory of the follower is then calculated from Newton's laws of motion to either pass through the target coordinates or at least a safe position behind the target position. The relative relationship between the current speed and position of the follower and its target speed and position determines the particular set of Newton equations that will be used. Generally the new section of the trajectory can include combinations of acceleration, deceleration, and constant speed.

As the car-following algorithm proceeds, redundant nodes are removed by a filtering process that ensures efficiency in the trajectory fitting. The existence of the complete vehicle trajectory in the simulation means that only those vehicles that affect the controller need to be retained at any time. Generally this includes only the vehicles that have hit the first detector. The simulation therefore is actually dealing with a relatively small number of vehicles at any time.

The vehicle simulation proceeds through a moving window upstream from the stop line, with vehicles processed in order of their position regardless of lane. Green approaches running simultaneously are processed together in the same window. This simplifies the gap-checking procedures in permissive green movements for left turners. The same window format handles a permissive green approach, a protected green approach, a red approach, or an approach with some lanes facing green and some facing red.

Lane changing is allowed in three situations. A through vehicle obstructed by a waiting left-turn vehicle can change into an adjacent through lane, arriving through vehicles will change lanes if a shorter queue is available, and turning vehicles will change into a short turning lane at the start of that lane.

Permissive left-turn vehicles may cross any number of opposing lanes. They are allowed an early start at the beginning of the green and a late turn on yellow. The default values of the probabilities of these maneuvers have been calibrated from field studies but can be changed by the user. Both right- and left-turning vehicles turn at given turning speeds that are derived from the turning radius specified by the user.

There are 100 randomly assigned driver types and driver reaction times; gap-acceptance probability of an early left turn and lane changing are all functions of driver type.

The simulation code is completely structured such that major changes or modifications can be made to one component without affecting other components. The signal controller is currently set up for a one- or two-ring standard NEMA controller. This module could be easily modified to change the existing controller or add a new type controller without affecting the remainder of the model. Similarly the detectors and vehicle actuations have their own module. New detector combinations or actuation procedures, or both, can be easily added without changing the main model.

The intersection simulation has been operating under a wide variety of phasing and detection scenarios. Its real time to computer time ratio is between 1,000 to 1 and 8,000 to 1 for the VAX 8600.

Output Module: OUTPUT

This module summarizes the model outputs including values for the measures of effectiveness and the optimal parameter settings. The overall economic benefit of the improvement is presented.

CALIBRATION AND VALIDATION

Validation of EVIPAS has been undertaken by comparing the simulation with field studies at 10 existing traffic-actuated signalized intersections. Data were collected on traffic volumes, vehicle types, vehicle speeds, stopped delay by approach lane, phase and phase duration, intersection geometry, and timing parameter settings.

All intersections sampled were located across the state of Pennsylvania and included the following types:

1. Fully actuated eight-phase with multilane approaches on the main line.
2. Fully actuated five-phase with volume density and multilane approaches on the main line, with and without volume density.
3. Fully actuated two-phase with permissive left turn.
4. Fully actuated three-phase with a permissive left turn on a multilane approach (i.e., at least two through lanes opposing the permissive left turn).
5. Fully actuated three-phase with leading left turn.
6. Semi-actuated.

For each intersection in the field study, the simulation was calibrated for one data set and then validated by using one or two additional data sets.

Two types of data were compared: the signal timing and the stopped delay of the traffic. The timing comparisons included the average length of each phase and the average cycle length.

TABLE 1 MODEL VALIDATION—SIGNAL TIMING (sec) (INTERSECTION OF ROUTE 19 AND WARRENDALE ROAD, WARRENDALE, PENNSYLVANIA, FIVE-PHASE FULLY ACTUATED)

Data Set	Phase	1+5	2+5	1+6	2+6	3	Cycle
1	Field	13.6	7.9	10.9	26.8	21.0	56.0
	Model	11.2	8.4	7.1	26.1	19.6	55.7
2	Field	13.4	13.7	11.9	24.4	20.8	52.9
	Model	11.2	6.8	9.2	26.2	19.9	56.7
3	Field	14.1	8.5	10.7	29.6	26.1	68.2
	Model	11.2	8.7	7.2	31.5	21.2	64.9

TABLE 2 MODEL VALIDATION—AVERAGE STOPPED DELAY (sec) (INTERSECTION OF ROUTE 19 AND WARRENDALE ROAD, WARRENDALE, PENNSYLVANIA, FIVE-PHASE FULLY ACTUATED)

Data Set	Approach	Lanes	Movement	Field	Model	Volume (vph)
1	SB	2	Through	14	8	450
	SB	1	Left	22	22	59
	WB	1	All	16	12	94
	NB	2	Through	8	5	425
	NB	1	Left	19	19	73
	EB	1	All	22	16	115
2	SB	2	Through	14	7	472
	SB	1	Left	25	26	89
	NB	1	All	14	18	125
	NB	2	Through	8	6	515
	NB	1	Left	28	18	63
	EB	1	All	23	16	82
3	SB	2	Through	11	7	630
	SB	1	Left	32	22	108
	WB	1	All	17	15	150
	NB	2	Through	11	6	762
	NB	1	Left	25	22	67
	EB	1	All	27	29	137

The EVIPAS model replicated the field data very closely. Generally the phase lengths and cycle lengths were within 5 percent of the field results.

The average stopped delay of the traffic was compared for each lane group of each approach. The delay comparisons generally were within 20 percent of the field data. Most cases in which the delays did not agree very well could be traced to irregular detector performance, or local peculiarities in driver behavior with regard to the observance of lane directions.

Tables 1 through 8 give examples of the comparisons between field observations and the computer model.

CONCLUSION

The EVIPAS model is showing considerable promise for the evaluation and optimization of a variety of types of traffic signal installations. The development efforts have concentrated on producing a general capability to model most geometric, traffic, and control scenarios and to provide an efficient and rigorous optimization structure.

The model has been programmed to allow future changes in the controller or detection, or both, without any modifications to the main program. Testing and validation of EVIPAS has shown that it replicates observed vehicle behavior and controller phasing.

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TABLE 3 MODEL VALIDATION—SIGNAL TIMING (sec) (INTERSECTION OF ROUTE 212 AND PERITAN STREET, UNIONTOWN, PENNSYLVANIA, SEMI-ACTUATED)

Data Set	Phase	1	2	Cycle
1	Field	19.4	84.8	104.2
	Model	18.8	82.8	101.0
2	Field	20.0	81.9	101.9
	Model	19.0	81.5	99.9

TABLE 4 MODEL VALIDATION—AVERAGE STOPPED DELAY (sec) (INTERSECTION OF ROUTE 212 AND PERITAN STREET, UNIONTOWN, PENNSYLVANIA, SEMI-ACTIVED)

Data Set	Approach	Lanes	Movement	Field	Model	Volume (vph)
1	SB	1	All	17	17	38
	WB	1	All	1	2	173
	NB	1	All	17	22	19
	EB	1	All	3	2	231
2	SB	1	All	19	19	42
	WB	1	All	4	2	223
	NB	1	All	19	9	26
	EB	1	All	3	2	307

Note: EB, WB is the main highway and is not actuated.

TABLE 5 MODEL VALIDATION—SIGNAL TIMING (sec) (INTERSECTION OF ROUTE 30 AND ROUTE 48, IRWIN, PENNSYLVANIA, EIGHT-PHASE FULLY ACTUATED)

Data Set	Phase	1+5	2+5	1+6	2+6	3+7	4+7	3+8	4+8	Cycle
1	Field	23.7	None	14.7	50.6	23.0	7.5	2.8	35.2	145.3
	Model	21.7	3.5	13.9	51.0	19.8	10.1	6.8	38.2	145.9
2	Field	23.1	None	13.4	47.2	20.4	8.0	4.5	36.6	139.6
	Model	21.1	4.1	13.1	54.5	20.5	16.3	3.6	38.8	153.6

TABLE 6 MODEL VALIDATION—AVERAGE STOPPED DELAY (sec) (INTERSECTION OF ROUTE 30 AND ROUTE 48, IRWIN, PENNSYLVANIA, EIGHT-PHASE FULLY ACTUATED)

Data Set	Approach	Lanes	Movement	Field	Model	Volume (vph)
1	SB	2	All	62	65	403
	WB	3	All	39	37	642
	NB	2	All	NA	48	384
	EB	3	All	33	31	651
2	SB	2	All	65	69	566
	WB	3	All	43	40	596
	NB	2	All	NA	56	401
	EB	3	All	52	48	1105

TABLE 7 MODEL VALIDATION—SIGNAL TIMING (sec) (INTERSECTION OF ROUTE 322 AND CHURCH STREET, STATE COLLEGE, PENNSYLVANIA, TWO-PHASE FULLY ACTUATED)

Data Set	Phase	1	2	Cycle
1	Field	43.2	13.4	56.6
	Model	42.9	15.9	58.2
2	Field	41.9	15.7	57.6
	Model	42.3	15.8	57.5

TABLE 8 MODEL VALIDATION—AVERAGE STOPPED DELAY (sec) (INTERSECTION OF ROUTE 322 AND CHURCH STREET, STATE COLLEGE, PENNSYLVANIA, TWO-PHASE FULLY ACTUATED

Data Set	Approach	Lanes	Movement	Field	Model	Volume
1	SB	2	All	3	3	984
	WB	1	All	21	17	62
	NB	2	All	4	3	388
	EB	1	All	17	16	132
2	SB	2	All	5	3	1097
	WB	1	All	19	18	108
	NB	2	All	5	2	452
	EB	1	All	18	29	115

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BORROWING LIBRARY REPORT:
Date received _____ Date returned _____
Returned via ________ Insured for $ ____
Payment provided $ ____________

RENEWALS:
Date requested ____________
New due date ____________
Renewal denied ____________