

# Challenges for Qualitative Electrical Reasoning in Automotive Circuit Simulation

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## Abstract

Qualitative reasoning about electrical systems has reached a level of achievement which allows it to be used for applications on realistic automotive circuits. The type of circuits for which it is most effective can be characterised as circuits with a single steady state for each combination of inputs. Many automotive circuits with more complex overall behaviour can be approximated using this type of modelling by representing the behaviour of more complex components only at a functional level, or by judicious use of simplifying assumptions.

This paper will consider examples of circuitry in modern cars where such approximations of behaviour are unsatisfactory, and will examine the modelling issues that are thrown up by these cases, in order to identify challenges for qualitative electrical reasoning against which future advances in the field can be assessed.

## Introduction

Electrical circuits were among the earliest devices to be modelled by AI researchers, giving qualitative reasoning about electrical systems a legacy of some two decades of research. This lengthy development is beginning to pay dividends in industrial applications.

Over the past six years, we have developed the FLAME system to perform failure mode and effects analysis [Price 96, Price and Pugh 96] and sneak circuit analysis [Price, Snooke and Landry 96]. Within the last two years, automotive engineers working in consultation with researchers have applied the FLAME system to the different circuits in a modern car. This has provided a breadth of modelling experimentation that exists for very few other qualitative reasoning systems.

This paper takes stock of what has been done in modelling electrical circuits, and look at what further work needs to be done, based on the experience of the FLAME system. This experience is confirmed by the similar work being done by Mauss and Neumann [Mauss and

Neumann 95, Mauss and 96] in modelling automotive electrical circuits. The paper considers what has been achieved in modelling car electrical systems, the areas where improvements are needed, and the challenge of developments in the way in which car subsystems are implemented.

## Qualitative electrical reasoning - state of the art

### Basic Strategy

In order to persuade automotive engineers to use qualitative reasoning, it must be painless for them to build qualitative models of the circuits as they are being designed. This means that the qualitative models must use the same types of components that the engineers are used to dealing with, and that component descriptions must be reusable.

The underlying algorithms performing reasoning about electrical flow only use connectivity information, and the circuit topology used these algorithms will change as the state of components change. This has led to two levels of reasoning being employed.

**Higher level reasoning:** From the description of each component in the circuit, and knowledge of that component's state, generate a static network of connected resistances representing the electrical connectivity of the circuit at this point in time.

**Lower level reasoning:** Evaluate the static network, and assign new states to each component.

These two levels are linked by a simulation controller which applies the changes in activity from the lower level to the circuit description at the higher level and generates a new topology for evaluation at the lower level if necessary.

In our own work on the FLAME system, the lower level reasoning is based on [Lee and Ormsby 93], and is described in [Price and Pugh 96]. The higher level reasoning employs component descriptions that describe the internal topology of a component in different states and

under different failure modes. Examples of component descriptions are given in [Pugh and Snooke 96]. A component description consists of:

**Terminals.** Terminals are the inputs and outputs for the component. So, for example, an open relay has four terminals, two to the coil, and two to the relay switch. They are the points where other components can connect to this component.

**Internal topology of component.** The functionality of the component is determined in terms of links between terminals. These links can contain resistances which can change according to the state of other parts of the component.

**Dependencies.** Dependencies define how the internal resistances of a component change as the state of the other parts of the component change. If the open relay has two resistances, one for its coil and one for its switch, then one dependency would be that when the state of the coil was "Active" (current is flowing through it) then the value of the switch resistance is zero (the switch is closed).

**External states.** As will be seen in the next section, there are cases where the function of a component cannot be completely encapsulated, and the "no function in structure" rule has to be violated to obtain the desired behaviour. External states make information about the component's internal state available to other components. Engineers are warned to use this feature only under certain conditions in order to ensure that their results are meaningful.

**Failure modes.** Topology and dependencies can be redefined for different failure modes, so that the component acts appropriately when failures are being simulated.

In Mauss and Neumann's work, the lower level reasoning is based around rebuilding the static network of resistances as a series-parallel-star (SPS) tree. This allows easy evaluation of circuit activity, and enables the use of quantitative information if it is available. The higher level reasoning does not seem as well developed as the component descriptions outlined above, but certainly could be extended to provide similar coverage.

One area of uncertainty about the lower level reasoning is whether Mauss and Neumann's choice of representation is more efficient as the topology of the network changes. There are certainly cases where changes to circuit topology will only mean changing a small part of the star network. However, the complexity of the mapping

between the original circuit and the SPS tree means that it is not always possible to tell what changes to the SPS tree should be made for a change in circuit state, and so it may be necessary to rebuild the SPS tree completely after each change.

## Coping with complex behaviour

The FLAME system has been used to simulate the electrical systems of modern automobiles, and is able to produce reasonable results for 85% of the circuitry. For many of the circuits, some modelling compromises are necessary, and this section gives examples of the kinds of modelling strategies that have been employed in order to produce useful results.

**Encapsulate complex behaviour in a component.** This is the most common way of dealing with complex components. For example, where modern cars use ECUs (computerised control) to switch circuits, it is not necessary, or in many cases even desirable, to model the software that is performing the switching. The relevant behaviour of the ECU can be modelled as connections between ECU terminals with resistances that switch between zero and infinity. This strategy fits in well with the two levels of reasoning outlined in the previous section. It can also work for non-electrical components with switching behaviour.

**Distribute complex behaviour among several components.** For example, because of the qualitative nature of the simulation, effects which depend on quantitative values cannot be directly modelled. For instance, this happens in some windscreen wipe systems, where a multi-way switch changes the value of a resistance, and an ECU reads an analogue value on a line to decide on the speed of the windscreen wiper. This can be achieved by a mild violation of the "no function in structure" principle, where you have two linked components, the switch and the ECU. The switch sets an external state giving its analogue value, and the ECU reads that analogue value from the switch. It only does this if the wire on its terminal coming from the switch is ACTIVE. This allows it to deal correctly with failure conditions such as the wire failing open.

**Simplify the complex behaviour so that it is manageable.** Electronic cruise control systems contain fairly complex algorithms for deciding what to do, but for examining electrical failures, they can be simplified to three conditions: above desired speed, below

desired speed and at desired speed. This allows the basic behaviour of the cruise control to be exercised, without consideration of much unnecessary detail.

**Ignore the complex behaviour altogether.** When performing failure mode and effects analysis (FMEA) on the electrical circuitry of a car, it is possible to ignore some phenomena altogether, and still produce a reasonable FMEA report. Take an indicator light for example. The light will flash on and off when the circuit is working correctly. However, the overall behaviour of the circuit can be obtained by treating the lamp as a "normal" lamp rather than a flashing one.

This section has considered the compromises needed in order to be able to model automotive circuits with the FLAME system. The next section will look at how modelling can be extended to make some of those compromises unnecessary.

## Improving Qualitative Reasoning of Electrical Circuits

The number of compromises needed in order to successfully model automotive electrical circuits can be reduced by improving the range of phenomena that can be modelled. This section will consider the areas in which qualitative electrical reasoning needs to be extended in order to improve modelling capabilities and to be able to model some of the other 15% of circuits that cannot be usefully modelled now.

### Recent automotive design

For many years most automotive circuits followed the same basic pattern of the battery providing power to devices such as lamps and motors via sets of switches. The circuits of some high power devices had indirect control via relays to lower switch ratings and the required amount of highly rated cable under the dashboard (as illustrated in figure 1).

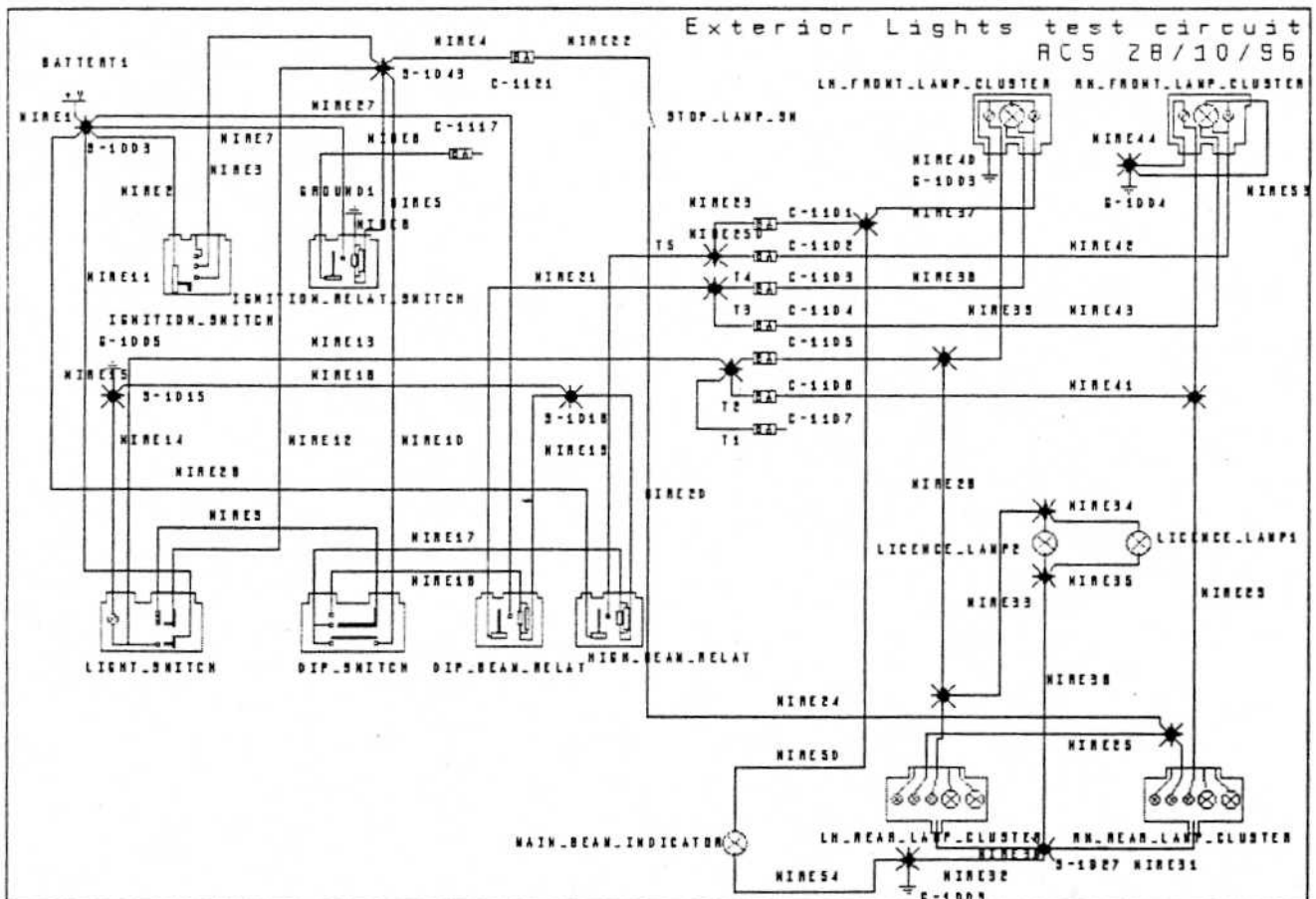


Figure 1 : Traditional lighting circuit

All this has changed recently, with many circuits following the pattern of a network of ECUs, each attached to a number of sensors (including button panels, keypads, and potentiometer for user input) and actuators. The sensor signals are thus processed and shared via a digital bus to other modules all of which ultimately control some actuators performing a wide range of tasks ranging from electric windows to fuel injectors. This type of system combines a number of the problems highlighted in this section, and these problems will now be itemized in the context of the column-mirror example in figure 2.

- There are many different types of signal from the sensors representing quantities in different ways. Typical methods include analog, pulsed amplitude modulated, pulse width modulated, frequency modulated etc.
- The digital bus connecting the modules has complex error detection and correction itself. Individual modules know the status of network connections and other modules at any point in time and adjust behaviour accordingly.
- Fail safe and/or default modes are incorporated in many modules to manage failure situations, and many modules have power down or sleep modes to save power.
- Feedback loops exist both as indirect loops (actuators affect sensors via other physical quantities) and direct feedback (ECU devices detect their own outputs or outputs of others).
- Many ECU's have complex internal empirically defined lookup tables to control behaviour (especially engine/gearbox management).
- Many actuators have a lot of built-in driver circuitry to provide complex control. This circuitry is built into the actuator by the component supplier, and has to be treated as a black box by the circuit designer.

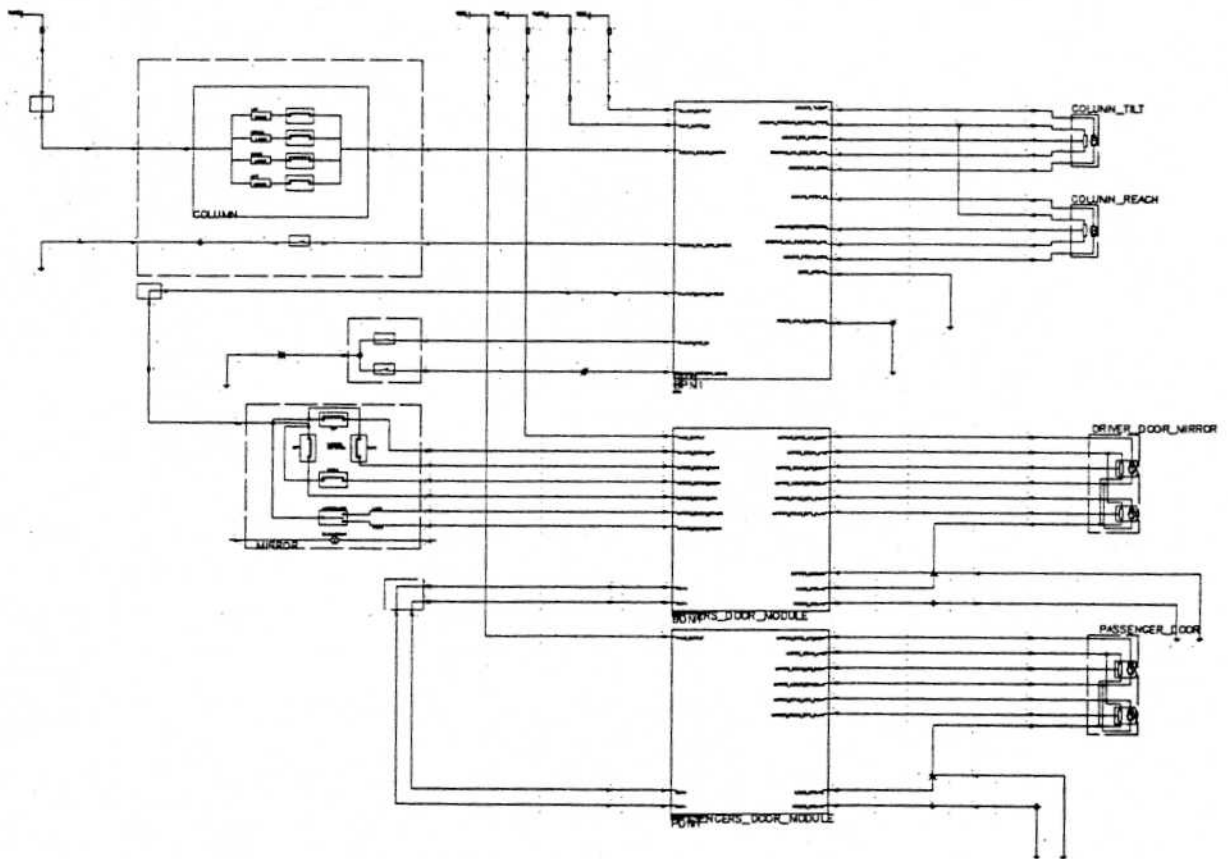


Figure 2 : Sensor/ECU/actuator based column mirror circuit



## Dynamic aspects

Circuits which contain continuously changing values – electrical feedback loops, oscillators, power on reset circuits – cannot be directly simulated because there is no representation of energy storage, or of the explicit rate of change of the energy variables.

Where the behaviour of components can be made into a discrete set of states, simulation can be achieved by using the simulator in a multi pass mode, with changes being made to the topology of the resistance network after each pass.

In this way a capacitor is modeled in either a charged or a discharged state, with either a infinite or zero resistance, and the change of state is made based on the existence of current flow through it. This enables the representation of the power-on-reset circuit's major change in state, along with the correct behaviour of short or open circuits in the circuitry surrounding the capacitor.

Other effects such as the long term effect of drawing charge from a battery are not currently considered, although it should be possible to model these. Also, if simulation was extended into other domains such as hydraulic, the issue of modelling capacity would become more relevant than it is in the electrical domain.

## Functions which cannot be linked to qualitative values

Typically the qualitative values utilized in the simulation (ACTIVE / INACTIVE, or FORWARD / INACTIVE / REVERSE where current direction is significant) are adequate to determine the presence or absence of function. Occasionally however the qualitative value set cannot represent the required functionality. This problem commonly occurs in situations where a resistor bank is used to multiplex a number of separate signal functions to some control circuitry.

A related situation occurs when the 'amount' of functionality is not related to power dissipation, and is not a monotonic function. Simply simulating the boundary conditions does not allow any assumptions concerning intermediate operation (some sensors may exhibit these behaviors). In these situations the inclusion of new key values raises many simulation issues perhaps indicating that a quantitative approach may be required in these situations.

Finally in the category of functional artifacts related to the qualitative analysis, there are situations where a small current indicates some component is ACTIVE without taking into account that the amount of current concerned is too small to actually cause the indicated functionality. Two examples of this have occurred in our experience of simulating circuits:

1) An ECU leakage current caused a relay coil to activate. In practice, the size of the current would have been far too small to activate the coil.

2) Failure of a ground stud caused a current to flow in a warning lamp in series with several large (normal) loads. In the simulation, this resulted in lighting the lamp, although in practice the voltage drop would be too small to produce any light.

An improved analysis which considers the changes in current paths and changing path resistance as well as qualitative voltage drop might alleviate some such problems.

## Improved behavioral substitutions

Removing the non electrical behaviors from the electrical model might help simplify the simulation and clean up the abstraction. The operation of switches (mechanical), magnetic effects in relays and ECU (logical/information) might be best modeled as a more abstract behaviour with well defined links to control the structure.

The problems of ECU components controlled by internal empirical lookup tables can be reduced by including simple versions of these as part of the controlling state machine. If it is required to model failure modes for these devices then additional behaviour can be included to represent the effect of each new failure.

## Alternative quantitative effort/flow models

Recently more circuits contain electrical structures which do not readily fall into the 'power electrical' category that our representation supports. An example of this is Control Area Network bus utilized for information transfer between modules in the automotive environment. In these situations we are interested in the higher level effects of the encoded protocol, rather than the electrical values, which require lots of interpretation.

Digital logic signals are becoming more common and again have characteristics which make simulation as a resistance network difficult not least due to the importance of voltage rather than current as the meaningful signal. We can currently utilize the upper level dependency expressions combined with a simplified electrical interface to model combinatorial logic devices although the expressions can get fairly complex even for relatively simple devices. For sequential logic we have a real problem due to the difficulty

of ordering the expressions. The solution appears to be to use the state machine representation of sequential logic, since this approach has often been used in the past in the design of such devices. With this approach there will be only a very much simplified electrical model present and in the future it may be necessary to move up a level of abstraction and consider the information flow and signal through the system rather than voltages and currents.

## Aggregation

For some kinds of design analysis (e.g. a complete sneak circuit analysis), it is necessary to perform simulation across the whole circuitry of a car at once. This involves simulating a circuit much larger than any separate subsystem circuit. Fortunately, the requirement for simulating very large networks has arisen at the same time as the restructuring of schematics into a hierarchical format. It may be possible to convert large sections of the hierarchy into a homogenized representation indicating only the equivalent resistance network. The analysis would then be greatly speeded up for each simulation, with the requirement that only parts of the hierarchy containing failures need be simulated in detail.

## Conclusions

The automotive domain has already proven a useful testing ground for practical qualitative modelling and reasoning about electrical circuitry. It has provided promising results on industrial systems, and has produced applications that have been accepted by industry.

A number of aspects of the present state of qualitative electrical simulation have been considered together with examples of where improvement or a different approach is necessary to deal with specific electrical constructions found in today's automotive circuits and the challenges of tomorrow's automotive circuits.

As the complexity of modern cars increases, the automotive domain is providing challenges that reach to the heart of the qualitative reasoning endeavour, highlighting issues of compositionality, modelling choices, temporal reasoning and the trade-offs that have to be made in order to apply qualitative reasoning. We anticipate that solutions to these challenges may be of use in other areas of qualitative reasoning.

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