Hindawi
Modelling and Simulation in Engineering
Volume 2018, Article ID 5986826, 5 pages
https://doi.org/10.1155/2018/5986826

Research Article

Discrete Event Simulation-Based Reliability Evaluation of a Traffic Signal Controller

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Received 11 February 2018; Revised 9 April 2018; Accepted 16 May 2018; Published 11 June 2018

Academic Editor: Zhiping Qiu

A mission reliability evaluation methodology for a signal traffic controller is presented in this paper. To develop the new evaluation methodology, this paper combines the Discrete Event System Specification (DEVS) formalism which has been popular in manufacturing area for three reasons: (1) its features compatible with the object-oriented modeling; (2) its rigorous formal definition; and (3) its support for the specifications of discrete event models in a hierarchical and modular manner. By using the DEVS formalism, we construct a simulation model which takes into account not only the characteristics of a traffic signal controller but also the operating environment. Once a model is constructed, it is possible to perform simulation experiments. The proposed methodology computes the mission reliability of a traffic signal controller by using a simulation record, and this information plays a vital role in preparing optimized maintenance policies that maximize availability or minimize life cycle costs.

1. Introduction

Traffic signals (or traffic lights) are lights used to control the movement of traffic, and they are electronically operated control devices. The major objective of traffic signals is to control and coordinate to ensure that traffic moves as smoothly and safely as possible [1, 2]. Traffic signals alternate the right of way accorded to users by displaying lights of a standard color (red, green, and yellow) following a universal color code. Nowadays, most of traffic signals are electronically operated, and they are typically controlled by a "traffic signal controller" mounted inside a cabinet.

Figure 1 shows an illustration showing traffic signals and a traffic signal controller. Typically, a traffic signal controller has four major objectives: (1) maximizing the traffic handling capacity of roads; (2) reducing collisions and waiting time for both vehicles and pedestrians; (3) encouraging travel within the speed limit to meet green lights; and (4) reducing unnecessary stopping and starting of traffic. A traffic control system consists of three major units: (1) Display unit to display lights of a standard color (red, green, and yellow); (2) Detector unit to detect the presence of vehicles; and (3) Controller unit containing a microcontroller which receives the output data from sensors and controls the glowing of lights based on the programming.

Since a traffic signal controller is directly related to the safety issues, it is very important to have a proper maintenance plan. An unexpected failure of a traffic signal controller may cause serious damages to both vehicles and pedestrians. Service providers, who are responsible for maintaining the equipment performance, need to have optimized maintenance policies that maximize availability or minimize life cycle costs.

To construct a decent maintenance plan, it is essential to perform the reliability analysis of a traffic signal controller. The reliability of a system may be described as its ability to function under the stated conditions for a specified period [3–5]. Although, the definition can be applied to a single component, it is not sufficiently specific to be applied to a traffic signal controller that can be assigned to various missions under various environments. For this reason, we use the concept of a mission reliability to evaluate the reliability of a traffic signal controller. Mission reliability is the probability of nonfailure of the system in the time required to complete a mission profile [6, 7].

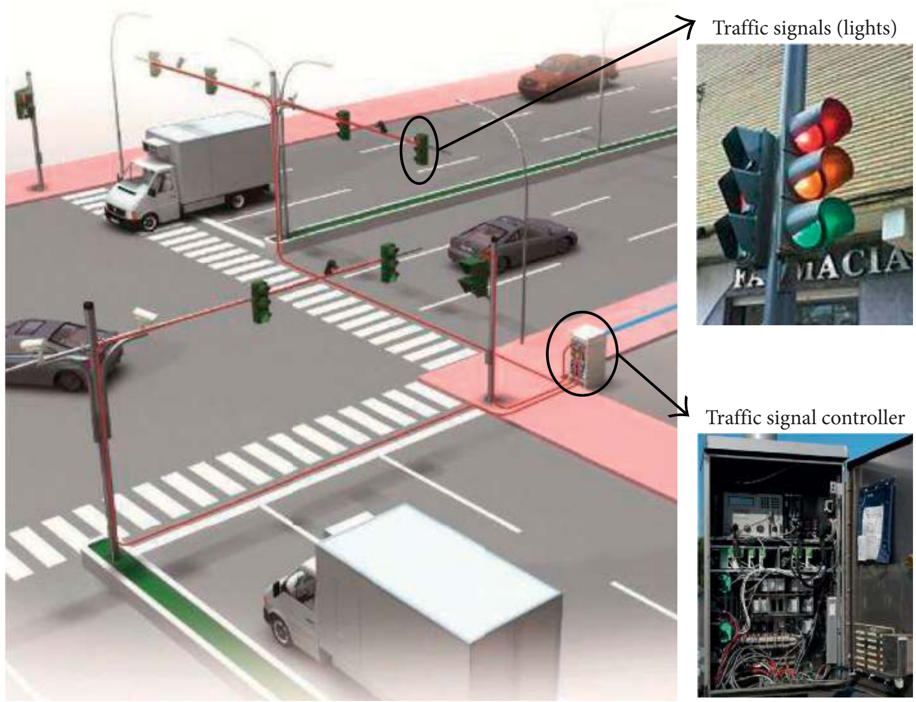


Figure 1: Traffic signals (traffic lights) and a traffic signal controller.

The mission reliability analysis has received substantial attention of many researchers for several decades. Previous research results can be categorized into three categories: (1) state-enumeration methods [8, 9]; (2) combinatorial methods [10, 11]; and (3) modular methods [12, 13]. While state-enumeration methods are able to handle many mission phases, combinatorial methods are able to effectively deal with the state explosion problem which is the weakness of state-enumeration methods. Modular methods complement the weaknesses of the two previous methods to some extent. Generally speaking, existing research results have limitations in dealing with the mission reliability of a large-scale system, such as a traffic signal controller.

Simulation technology is known to be effective to deal with a large-scale system. The objective of this paper is to apply the discrete event simulation technology to the evaluation of the mission reliability analysis of a large-scale system. The overall structure of this paper is as follows: Section 2 addresses the overall approach to the simulation-based reliability evaluation methodology for a traffic signal controller and Section 3 provides a detailed description of the proposed methodology. Finally, some concluding remarks are provided in Section 4.

2. Approach to Simulation Model Construction

The strategy of this paper is to evaluate the mission reliability of a traffic signal controller by using simulation technologies. To perform simulation experiments, it is necessary to construct a simulation model which takes into account not only the characteristics of a traffic signal controller but also the operating environment. However, there have been various modeling methodologies [14–18]. Among various modeling methodologies, the DEVS formalism has been popular because of three reasons: (1) its features compatible with the object-oriented modeling; (2) its rigorous formal definition; and (3) its support of the specifications of discrete event models in a hierarchical and modular manner. Considering these merits, this paper chooses the DEVS formalism for the simulation model construction.

Before addressing the construction of a simulation model, it is necessary to figure out the characteristics of the DEVS formalism. In DEVS formalism, there are two different kinds of models: (1) an atomic model is a basic model from which larger models are built and (2) a couple model represents how atomic models are connected in a hierarchical manner. Since a coupled model only provides the hierarchical structures, we focus on the atomic model which needs to describe not only the characteristics of a traffic signal controller but also the operating environment, as shown in Figure 2. Formally, an atomic model $\mathbf{M}$ is specified through a 7-tuple as follows:

$$\mathbf{M} = \langle \mathbf{I},\ \mathbf{O},\ \mathbf{S},\ \delta_{\text{int}},\ \delta_{\text{ext}},\ \rho,\ t_{\text{a}} \rangle, \tag{1}$$

where $\mathbf{I}$ is the input events' set; $\mathbf{O}$ is the output events' set; $\mathbf{S}$ is the sequential states' set; δ_{int}: $\mathbf{S} \rightarrow \mathbf{S}$ is the internal transition function; δ_{ext}: $\mathbf{Q} * \mathbf{I} \rightarrow \mathbf{S}$ is the external transition function; $\mathbf{Q} = \{(s,\ e) | s \in \mathbf{S},\ 0 \le e \le t_{\text{a}}(s)\}$ is the total state of $\mathbf{M}$; ρ: $\mathbf{S} \rightarrow \mathbf{O}$ is the output function; and t_{a}: $\mathbf{S} \rightarrow \mathbf{Real}$ is the time advance function.

As described above, an atomic model consists of three sets ($\mathbf{I}$, $\mathbf{O}$, and $\mathbf{S}$) and four functions ($\delta_{\text{int}}, \delta_{\text{ext}}, \rho,$ and t_{a}). In particular, the four functions are called the characteristic functions of an atomic model. The internal transition function (δ_{int}) specifies to which the next state the system will transit after the time given by the time advance function

(a) (b)

(c)

FIGURE 2: Various environment conditions for a traffic signal controller: (a) low temperature; (b) high temperature; (c) coastal environment.

(t_a) has elapsed. To handle external input events, we need the external transition function (δ_{ext}) which specifies how the system changes the state when an input is received. The output function (ρ) generates an external output just before an internal transition takes place. Each state s ($s \in \mathbf{S}$) has an associated time advance function (t_a) saying how long the system remains in a given state in absence of input events. If a system has more than one atomic model, individual models are connected to form a coupled model. In this paper, we use the DEVS formalism to construct a simulation model which takes into account not only the characteristics of a traffic signal controller but also the operating environment.

3. Mission Reliability of Traffic Signal Controller

Since a mission consists of multiple tasks, it is necessary to consider the task reliability for the mission reliability evaluation. In this paper, we define the "task reliability" as the probability of a task being performed for a period without failure. Let T denote the time to failure of a task, and $f(t)$ be the probability distribution function of T. At this time, the reliability of the task at time t can be defined as the probability that a facility will fail after time t ($t > 0$), and the task reliability can be stated as $R(t) = P(T > t) = 1 - \int_0^t f(x)\,dx$. In reliability engineering, an exponential distribution is popularly used, and we also assume that $f(t) = \lambda e^{-\lambda t}$, where parameter λ is a failure rate such that $1/\lambda$ is the mean time to failure. The usual dimension of a failure rate is (# of failures/1 million hours).

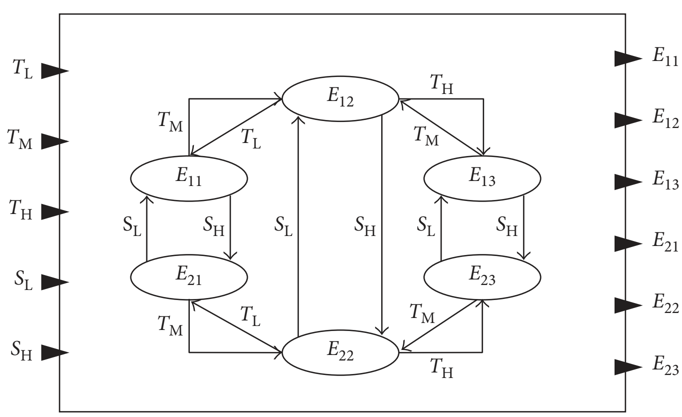
Usually, traffic signal controllers are operated outdoors, and their functionalities are affected by their environmental conditions, as shown in Figure 2. Various environmental stresses (temperature, salinity, vibration, and radiation) may affect the reliability of a traffic signal controller. This paper considers two major environmental factors, "temperature" and "salinity" for the mission reliability evaluation of a traffic signal controller. In the case of temperature, it is well known that the operating temperature affects the reliability of electronic components which make up a traffic signal controller. Other than temperature, it is necessary to consider the "airborne salinity" which refers to the content of gaseous and suspended salt in the atmosphere. The salt, deposited on the metal surface, accelerates the metal corrosion. Usually, the airborne salinity is measured in terms of deposition rate in units of mg/m^2/day.

Figure 3 shows an environmental table including the operating conditions of a traffic signal controller. The table contains six different environmental conditions (E_{ij}, combinations of three temperature conditions and two salinity conditions) and the corresponding failure rates (λ_{ij}) which are assumed to be obtained through a long-time experience and observation.

For the mission reliability evaluation, it is necessary to construct a simulation model which takes into account not only the characteristics of a traffic signal controller but also the operating environment. Figure 4 shows a DEVS atomic model for a traffic signal controller considering the operating conditions (E_{ij}) in terms of temperature and salinity. The model has six states (E_{ij}) and five inputs (T_L, T_M, T_H, S_L,

Airborne salinity (Deposition rate of NaCl) \ Temperature	Low temperature ($T < 0°C$)	Medium temperature ($0 < T < 30°C$)	High temperature ($30°C < T$)
Low salinity $S < 3$ mg/m^2/day	E_{11} $\lambda_{11} = 16$ times/1 million hours	E_{12} $\lambda_{12} = 20$ times/1 million hours	E_{13} $\lambda_{13} = 36$ times/1 million hours
High salinity $S > 3$ mg/m^2/day	E_{21} $\lambda_{21} = 34$ times/1 million hours	E_{22} $\lambda_{22} = 41$ times/1 million hours	E_{23} $\lambda_{23} = 64$ times/1 million hours

Figure 3: Environmental conditions and failure rates.



TSC = $<I, O, S, \delta_{int}, \delta_{ext}, \rho, t_a>$
$I = \{T_L, T_M, T_H, S_L, T_H\}$
$O = \{E_{11}, E_{12}, E_{13}, E_{21}, E_{22}, E_{23}\}$
$S = \{E_{11}, E_{12}, E_{13}, E_{21}, E_{22}, E_{23}\}$
$\delta_{ext}(E_{11}, T_M) \rightarrow E_{12}$
$\delta_{ext}(E_{11}, S_H) \rightarrow E_{21}$
$\delta_{ext}(E_{12}, T_L) \rightarrow E_{11}$
$\delta_{ext}(E_{12}, S_H) \rightarrow E_{22}$
$\delta_{ext}(E_{12}, T_H) \rightarrow E_{13}$
$\delta_{ext}(E_{13}, T_M) \rightarrow E_{12}$
$\delta_{ext}(E_{13}, S_H) \rightarrow E_{23}$
$\delta_{ext}(E_{21}, T_M) \rightarrow E_{22}$
$\delta_{ext}(E_{21}, S_L) \rightarrow E_{11}$
$\delta_{ext}(E_{22}, T_L) \rightarrow E_{21}$
$\delta_{ext}(E_{22}, S_L) \rightarrow E_{12}$
$\delta_{ext}(E_{22}, T_H) \rightarrow E_{23}$
$\delta_{ext}(E_{23}, T_M) \rightarrow E_{22}$
$\delta_{ext}(E_{23}, S_L) \rightarrow E_{13}$
$\rho(E_{ij}) \rightarrow E_{ij}$
$t_a(E_{ij}) \rightarrow \infty$

Figure 4: DEVS model for a traffic signal controller under various environmental conditions.

and S_H). Inputs may be interpreted as "sensors" monitoring the environmental conditions. Among them, T_L, T_M, and T_H represent temperature conditions: low temperature, medium temperature, and high temperature, respectively. Similarly, S_L and S_H represent salinity conditions: low salinity and high salinity, respectively.

Once a simulation model is constructed, we need to have a simulation engine which is able to execute the simulation model. The implementation algorithm of the simulation engine can be found in books [14, 18] and on the website (https://en.wikipedia.org/wiki/DEVS). One practical advantage of using DEVS formalism is that it is realized using the simulation environment, DEVSIM++ [14], and as a result, we can simulate a DEVS model without implementing a simulation engine. Each simulation experiment generates a simulation log file containing a record of the simulation, which is a sequence of total states, $\mathbf{Q_i} = \{(s_i, e_i) | s_i \in \mathbf{S}, 0 \le e_i \le t_a(s_i)\}$, where $1 \le i \le n$. A single state means a task, and it (s_i, e_i) includes two kinds of information: (1) the failure rate (λ_{ij}) according to the state (E_{ij}), and (2) the elapsed time of the state ($t = e_i$). Then, the task reliability becomes $R(t) = e^{-\lambda t}$. In this way, a task reliability can be obtained from a simulation log file. Since a mission consists of multiple tasks, it can be computed by simply multiplying the all related task reliabilities.

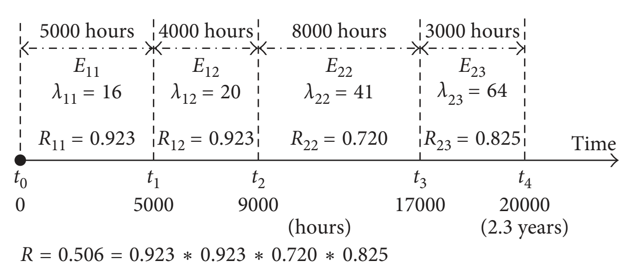


Figure 5: Mission reliability evaluation of a traffic signal controller.

A simulation record is given in Figure 5. The state history includes four states (E_{11}, E_{12}, E_{22}, and E_{23}), and their corresponding failure rates (λ_{11}, λ_{12}, λ_{22}, and λ_{23}) can be seen in Figure 3. At this time, we assume that there are no statistical dependencies among consecutive phases. The total operating time is 20,000 hours (2.3 years) consisting of four state periods (5000 hours at E_{11}, 4000 hours at E_{12}, 8000 hours at

E_{22}, and 3000 hours at E_{23}). As mentioned above, the task reliability is $e^{-\lambda t}$. By using the equation, we can compute all task reliabilities ($R_{11} = 0.923$, $R_{12} = 0.923$, $R_{22} = 0.720$, and $R_{23} = 0.825$). As a result, the mission reliability becomes 0.506, as shown in Figure 5. In this way, we can evaluate the mission reliability of a traffic signal controller, and this information plays a vital role in preparing optimized maintenance policies that maximize availability or minimize life cycle costs.

4. Discussion and Conclusions

Traffic signal controllers are directly related to the safety issues, it is very important to have a proper maintenance plan to ensure the safety of vehicles and pedestrians. To make a decent maintenance plan, it is necessary to evaluate the mission reliability of a traffic signal controller. Most of previous research results on mission reliability use analytical methods which are not easy to handle a large-scale system such as a traffic signal controller. This paper combines the discrete event simulation technology to develop a new mission reliability evaluation methodology for a signal traffic controller. However, the discrete event simulation area has numerous modeling techniques, and this paper employs the DEVS formalism because of three beneficial reasons: (1) its features compatible with the object-oriented modeling; (2) its rigorous formal definition; and (3) its support of the specifications of discrete event models in a hierarchical and modular manner.

The simulation model for a traffic signal controller has been constructed by using the DEVS formalism, and it takes into account not only the characteristics of a traffic signal controller but also the operating environmental conditions. This paper considers two major environmental factors, "temperature" and "salinity" for the mission reliability evaluation of a traffic signal controller. Once a simulation model is constructed, it is possible to perform simulation experiments by making use of the DEVS simulation engine. Each simulation experiment generates a simulation log file containing a record of the simulation. The proposed methodology computes the mission reliability of a traffic signal controller by using a simulation record, and this information plays a vital role in preparing optimized maintenance policies that maximize availability or minimize life cycle costs.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by a grant (18CTAP-C129828-02) from Infrastructure and Transportation Technology Promotion Research Program funded by Ministry of Land, Infrastructure and Transport of Korean Government.

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