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► **To cite this version:**

G.G Pivnyak, V.V Kravets, K.M Bas, M.S Zubariev, L.A Tokar. Analysis of Cost Efficiency in the Context of a Filling and Charging Station for Hybrid Vehicles. *Mechanics, Materials Science & Engineering Journal*, 2017, 10.2412/mmse.95.86.168 . hal-01966416

HAL Id: hal-01966416

<https://hal.science/hal-01966416>

Submitted on 28 Dec 2018

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Analysis of Cost Efficiency in the Context of a Filling and Charging Station for Hybrid Vehicles

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DOI 10.2412/mmse.95.86.168 provided by Seo4U.link

Keywords: hybrid vehicles, transition probability matrices, transition value matrices, mathematical expectation of Markov process value.

ABSTRACT. A method of the analysis of cost efficiency in the context of filling and charging stations for hybrid vehicles is proposed. Dynamic model of random Markov process for hybrid vehicles maintenance in the form of asymmetric state graph with four nodes is constructed. Relevant mathematical model of random Markov process in the form of recurrent quartic matrix format is being developed. Matrix of transition values to reconstitute and store both mechanical and electrical subsystems of hybrid vehicles, mathematical expectations of values of certain transitions is formed. A matrix of transition values to re-establish and store both mechanical and electrical subsystems of hybrid vehicles; mathematical expectations of values of certain transitions as well as mathematical expectation of a random Markov process value on the whole are introduced.

Introduction. Global environmental problems are closely connected with energy efficiency of vehicles. Basic tendency concerning the improvement of energy efficiency of vehicles is forecasted and implemented in the field of the progress of electromechanical systems [1-3]. More specifically, hybrid cars and their companion infrastructure (i.e. filling and charging stations) are developed.

A wide range of emerging problems are solved wholistically relying on fundamental results represented, for instance, in monographs [4, 5]. In this context, random processes within complicated systems (technical, biological) modeling, their reliability and cost-efficiency estimation are performed on the basis of Markov chains (discrete, continuous) [6-8]. Following the continuity in the material statement, the paper uses symbols and formulas mentioned in [6, 9].

Formulation of the problem. Filling and charging station for the maintenance of hybrid cars is under consideration. Hybrid car is represented as an engineering system consisting of two independent subsystems (i.e. bisystem):

- 1) Mechanical subsystem involving internal combustion engine and its companion equipment;
- 2) Electrical subsystem involving power-wheel and its companion equipment.

Maintenance process of a stream of hybrid cars at a filling and charging station is cyclic and random. For the considered problem, a period of cyclic process is taken to be twenty-four hours. The maintenance process involves activities connected with vehicle health check and recovery (filling, charging) of both mechanical and electrical subsystems. Each of the systems may be in either of the two lumped states:

- power capacity recovery state symbolized as \oplus ; and
- power capacity conservation state symbolized as \ominus .

Random transitions (steps) of the subsystems from one state to another are considered in the context of the discrete moments

$$t_k = k \cdot \Delta t(k) \quad (k = 0, 1, 2, \dots) \quad (1)$$

separated by $\Delta t(k)$ pitch (stage). At this point, the pitch distance determines the accuracy of the engineering problem as well as the amount of calculations being made. Substantiation of the pitch distance is the individual problem being solved depending upon specified problem both heuristically and with the help of strict mathematical calculating values [10]. The following is recommended: no more than one transition of the subsystems from one state to another should take place during $\Delta t(k)$ period. For the periodic random process, the $\Delta t(k)$ pitch should not exceed the period or it should be a multiple of the period. It may turn out to be expedient to select the pitch distance according to discrete time k , i. e. $\Delta t(k)$. To simplify the process of the engineering problem solving, as a first approximation, pitch distance of discrete time is set equal to an hour ($\Delta t = 1$). Then, those discrete moments, during which random transitions of hybrid vehicles from one state to another are recorded, can be identified using the simple formula:

$$t_k = k, \quad (2)$$

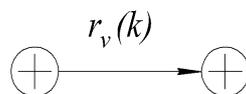
where $k = 0, 1, 2, 3, \dots, 24$; and

$$t_0 = t_{24}. \quad (3)$$

Depending upon the formulated conditions of the engineering problem under consideration, it is expedient to analyze dynamics of random process concerning the maintenance of hybrid vehicles as well as cost efficiency of a filling and charging station basing upon a theory of Markov random processes. The analysis involves the development of reasonable scheme of the process, adequate mathematical model as well as computational algorithm to model the process.

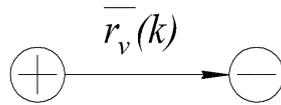
Dynamic scheme of random process of hybrid vehicles maintenance. In the process of independent maintenance of each subsystem of hybrid vehicle ($\nu = 1, 2$) following random transitions may take place at discrete t_k moments:

- recovery state of ν^{th} subsystem continues during following pitch; that is:



where $r_\nu(k)$ is the random event probability;

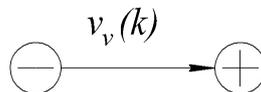
- recovery state of ν^{th} subsystem has been completed during k^{th} pitch; during following pitch, a transition to conservation state takes place; that is:



where $\bar{r}_\nu(k)$ is probability of contrary event. It is obvious that

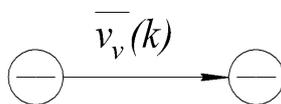
$$r_\nu(k) + \bar{r}_\nu(k) = 1; \tag{4}$$

- conservation state of ν^{th} subsystem during k^{th} pitch has been terminated; during following pitch, a transition to recovery state (recharging, refilling) takes place; that is:



where $v_\nu(k)$ is probability of the contrary event;

- conservation state of ν^{th} system has been continued during following pitch; that is:



where $\bar{v}_\nu(k)$ is the probability of opposite event. It is obvious that

$$v_\nu(k) + \bar{v}_\nu(k) = 1; \tag{5}$$

Probabilities of random transitions of each of the systems during discrete moments can be determined with the help of statistical methods as a result of processing of experimental data concerning specific filling and charging station functioning. Qualitative estimations of the probabilities are defined according to following approximate formulas:

$$r_\nu(k) \approx \frac{n_\nu^\oplus(k)}{N_\nu(k)}; \quad \bar{r}_\nu(k) \approx \frac{n_\nu^\ominus(k)}{N_\nu(k)}; \tag{6}$$

$$V_\nu(k) \approx \frac{m_\nu^\oplus(k)}{M_\nu(k)}; \quad \bar{V}_\nu(k) \approx \frac{m_\nu^\ominus(k)}{M_\nu(k)}; \tag{7}$$

where $n_v^{\oplus}(k)$ – is the number of cases corresponding to a transition of type one for ν^{th} system during k^{th} pitch;

$n_v^{\ominus}(k)$ – is the number of cases corresponding to a transition of type two for ν^{th} system during k^{th} pitch;

$m_v^{\oplus}(k)$ – is the number of cases corresponding to a transition of type three for ν^{th} system during k^{th} pitch;

$m_v^{\ominus}(k)$ – is the number of cases corresponding to a transition of type four for ν^{th} system during k^{th} pitch;

$N_v(k)$ – is the number of cases corresponding to recovery state of ν^{th} subsystem during k^{th} pitch;

$M_v(k)$ – is the number of cases corresponding to observation state of ν^{th} subsystem during k^{th} pitch.

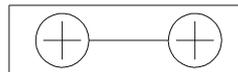
It should be noted that obvious equalities take place:

$$N_v(k) = n_v^{\oplus}(k) + n_v^{\ominus}(k); \tag{8}$$

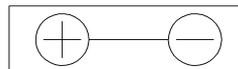
$$M_v(k) = m_v^{\oplus}(k) + m_v^{\ominus}(k). \tag{9}$$

In the process of hybrid cars maintenance at a filling and charging station, every of the two independently operating subsystems (mechanical subsystem and electrical one) can perform random transition from one state to another and back (states of recovery and observation) during discrete moments. On the whole, possible states of any hybrid vehicle can be determined with the help of diagram of states or according to generating function [8] at a rate defined in the form of 2^2 :

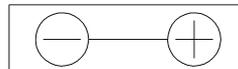
1) S_1 :



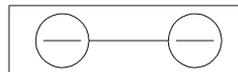
2) S_2 :



3) S_3 :



4) S_4 :



A sequence of random events connected with intermittent transitions of hybrid vehicle on the four demonstrated possible discrete states within the determined discrete moments may be a random process taking place in a discrete Markov chain [9]. It is convenient to illustrate dynamics of the process of hybrid vehicle transition at filling and charging station as of possible states using such an asymmetric state graph:

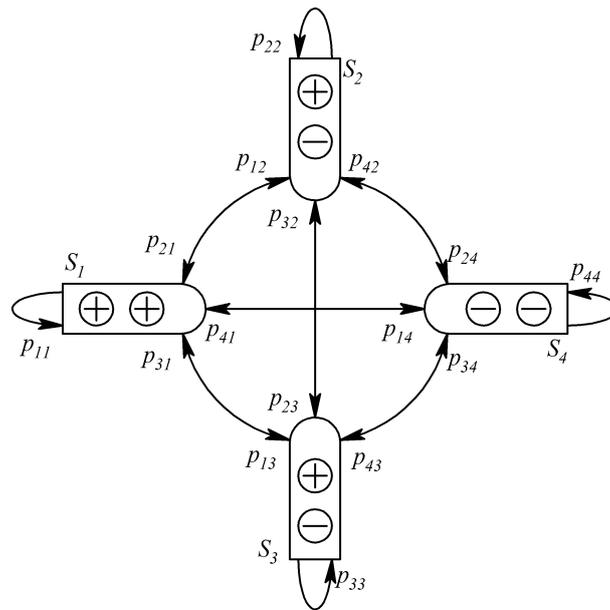


Fig. 1. Dynamic scheme of a random process concerning hybrid vehicle maintenance at a filling and charging station.

In this context, the number of peaks (states) and arcs (transition possibilities) within the asymmetric graph is determined as follows: $2^2 = 4$, $2^4 = 16$ respectively. The asymmetric graph of states as well as corresponding discrete nonuniform Markov chain is the dynamic scheme of random process of hybrid vehicles maintenance at a filling and charging station.

Matrix mathematical model of Markov random process concerning hybrid vehicle maintenance at a filling and charging station. According to the demonstrated graph of discrete states, nonuniform Markov chain, mathematical model of random maintenance process for hybrid vehicles is developed. The model is reduced to the recurrent matrix form of 4th order [9]:

$$P_{(4 \times 1)}(k+1) = P_{(4 \times 4)}(k) \cdot P_{(4 \times 1)}(k). \tag{10}$$

In this context, column matrix of possibilities $P_{(4 \times 1)}[S_j(k+1)]$ of the four states S_j ($j = 1, 2, 3, 4$) of a hybrid vehicle is determined during following $(k+1)^{th}$ pitch with the use of column matrix $P_{(4 \times 1)}[S_j(k)]$ of the bisystem probability of states during previous k^{th} and square matrix $P_{(4 \times 4)}(k)$ of the transition probabilities. Components of the square matrix of transition probabilities $P_{(4 \times 4)}(k)$ correspond to arches of the graph of state graph of discrete Markov chain; the components are determined as conditional probabilities with the help of statistically determined probabilities of random transitions of both mechanical and electrical subsystems of hybrid vehicles: $r_v(k)$, $\bar{r}_v(k)$, $v_v(k)$, $\bar{v}_v(k)$; that is

$$\begin{aligned} p_{11} &= r_1 r_2, & p_{21} &= r_1 v_2, & p_{31} &= v_1 r_2, & p_{41} &= v_1 v_2, \\ p_{12} &= r_1 \bar{r}_2, & p_{22} &= r_1 \bar{v}_2, & p_{32} &= v_1 \bar{r}_2, & p_{42} &= v_1 \bar{v}_2, \\ p_{13} &= \bar{r}_1 r_2, & p_{23} &= \bar{r}_1 v_2, & p_{33} &= \bar{v}_1 r_2, & p_{43} &= \bar{v}_1 v_2, \\ p_{14} &= \bar{r}_1 \bar{r}_2, & p_{24} &= \bar{r}_1 \bar{v}_2, & p_{34} &= \bar{v}_1 \bar{r}_2, & p_{44} &= \bar{v}_1 \bar{v}_2. \end{aligned} \tag{11}$$

It should be noted that sums of matrix columns $P_{(4 \times 4)}(k)$ and $P_{(4 \times 1)}(k)$ are normalized at each pitch of discrete time; that is:

$$\begin{aligned}
 p_{11} + p_{12} + p_{13} + p_{14} &= 1, \\
 p_{21} + p_{22} + p_{23} + p_{24} &= 1, \\
 p_{31} + p_{32} + p_{33} + p_{34} &= 1, \\
 p_{41} + p_{42} + p_{43} + p_{44} &= 1,
 \end{aligned}
 \tag{12}$$

and

$$\begin{aligned}
 P_1(k) + P_2(k) + P_3(k) + P_4(k) &= 1, \\
 P_1(k+1) + P_2(k+1) + P_3(k+1) + P_4(k+1) &= 1.
 \end{aligned}
 \tag{13}$$

The conditions enable analyzing stability (convergence) of the iteration process and controlling the accuracy of calculation procedures at each pitch (verification).

The problem is to determine probabilities of the four states of a hybrid vehicle at its following stage according to the probabilities of states at the previous pitch in the context of the preset boundary conditions. The boundary conditions are strictly determined initial ($k=0$) and final ($k \rightarrow \infty$) conditions of the hybrid vehicle. Initial state is determined as a result of diagnosing of both mechanical and electrical subsystems within the initial pitch. Final condition of hybrid vehicle maintenance is target-oriented; it is the achievement of stable state at certain pitch when both mechanical and electrical subsystems have already been recovered, operating in a standard mode and being conserved, i.e. state S_4 .

Maintenance process for hybrid vehicles at a filling and charging station is considered as a finite sequence of probabilities of random states within discrete moments. Nature and duration of random maintenance process of both mechanical and electrical subsystems, limited by the preset boundary conditions, can be determined as a result of calculation experiment according to the developed mathematical model in the form of nonuniform, discrete Markov chain.

Transition values for hybrid vehicles maintenance at a filling and charging station. Random values for the recovery and conservation of certain subsystems within each pitch of staying at a filling and charging station are characterized by following distribution laws:

- for a mechanical subsystem:

$$\begin{array}{c|cc}
 C_1 & c_1 & \bar{c}_1 \\
 \hline
 R_1 & r_1 & \bar{r}_1
 \end{array}
 \qquad
 \begin{array}{c|cc}
 L_1 & l_1 & \bar{l}_1 \\
 \hline
 V_1 & v_1 & \bar{v}_1
 \end{array}$$

- for an electrical subsystem:

C_2	c_2	\bar{c}_2	L_2	l_2	\bar{l}_2
R_2	r_2	\bar{r}_2	V_2	v_2	\bar{v}_2

In this context, C_1 and C_2 are discrete random values to recover both mechanical and electrical subsystems; L_1 and L_2 are discrete random values to conserve both mechanical and electrical subsystems; c_1 and c_2 are cost of time unit within the preset pitch while recovering both mechanical and electrical subsystems; l_1 and l_2 are time cost within the preset pitch while conserving both mechanical and electrical subsystems.

Depending upon discrete time, random maintenance values for mechanical ($\nu = 1$) and electrical ($\nu = 2$) subsystems of hybrid vehicles at filling and charging station at k^{th} pitch with $\Delta t(k)$ duration are determined statically according to the formulas:

$$c_\nu(k) = \frac{\sigma[n_\nu^\oplus(k)]}{\Delta t(k) \cdot n_\nu^\oplus(k)}; \quad \bar{c}_\nu(k) = \frac{\sigma[n_\nu^\ominus(k)]}{\Delta t(k) \cdot n_\nu^\ominus(k)}; \tag{14}$$

$$l_\nu(k) = \frac{\sigma[m_\nu^\oplus(k)]}{\Delta t(k) \cdot m_\nu^\oplus(k)}; \quad \bar{l}_\nu(k) = \frac{\sigma[m_\nu^\ominus(k)]}{\Delta t(k) \cdot m_\nu^\ominus(k)}. \tag{15}$$

In this context, $\sigma[n_\nu^\oplus(k)]$ is maintenance cost for ν^{th} subsystem within k^{th} pitch in those cases corresponding to the transition of type one (recovery-recovery);

$\sigma[n_\nu^\ominus(k)]$ is maintenance cost for ν^{th} subsystem within k^{th} pitch in those cases corresponding to the transition of type two (recovery-conservation);

$\sigma[m_\nu^\oplus(k)]$ is maintenance cost for ν^{th} subsystem within k^{th} pitch in those cases corresponding to the transition of type three (conservation-recovery);

$\sigma[m_\nu^\ominus(k)]$ is maintenance cost for ν^{th} subsystem within k^{th} pitch in those cases corresponding to the transition of type four (conservation-conservation).

Adequate mathematical expectations of values to recover and conserve both mechanical and electrical subsystems are:

$$\begin{aligned}
 M_{C_1}(k) &= c_1(k) \cdot r_1(k) + \bar{c}_1(k) \cdot \bar{r}_1(k); \\
 M_{L_1}(k) &= l_1(k) \cdot v_1(k) + \bar{l}_1(k) \cdot \bar{v}_1(k); \\
 M_{C_2}(k) &= c_2(k) \cdot r_2(k) + \bar{c}_2(k) \cdot \bar{r}_2(k); \\
 M_{L_2}(k) &= l_2(k) \cdot v_2(k) + \bar{l}_2(k) \cdot \bar{v}_2(k),
 \end{aligned}
 \tag{16}$$

Thus, they depend on discrete time k being assumed as constants within Δt interval.

Dimensions of a matrix of transition values of random maintenance process of hybrid vehicles at a filling and charging station depend on the number of arches of the asymmetric state graph, i.e.

$$C_{(4,4)}(k) = \begin{vmatrix} c_{11}(k) & c_{21}(k) & c_{31}(k) & c_{41}(k) \\ c_{12}(k) & c_{22}(k) & c_{32}(k) & c_{42}(k) \\ c_{13}(k) & c_{23}(k) & c_{33}(k) & c_{43}(k) \\ c_{14}(k) & c_{24}(k) & c_{34}(k) & c_{44}(k) \end{vmatrix}, \quad (17)$$

where

$$\begin{aligned} c_{11}(k) &= r_1(k) \cdot r_2(k) \cdot [c_1(k) + c_2(k)]; & c_{21}(k) &= r_1(k) \cdot v_2(k) \cdot [c_1(k) + l_2(k)]; \\ c_{12}(k) &= r_1(k) \cdot \bar{r}_2(k) \cdot [c_1(k) + \bar{c}_2(k)]; & c_{22}(k) &= r_1(k) \cdot \bar{v}_2(k) \cdot [c_1(k) + \bar{l}_2(k)]; \\ c_{13}(k) &= \bar{r}_1(k) \cdot r_2(k) \cdot [\bar{c}_1(k) + c_2(k)]; & c_{23}(k) &= \bar{r}_1(k) \cdot v_2(k) \cdot [\bar{c}_1(k) + l_2(k)]; \\ c_{14}(k) &= \bar{r}_1(k) \cdot \bar{r}_2(k) \cdot [\bar{c}_1(k) + \bar{c}_2(k)]; & c_{24}(k) &= \bar{r}_1(k) \cdot \bar{v}_2(k) \cdot [\bar{c}_1(k) + \bar{l}_2(k)]; \\ & & & (18) \\ c_{31}(k) &= v_1(k) \cdot r_2(k) \cdot [l_1(k) + c_2(k)]; & c_{41}(k) &= v_1(k) \cdot v_2(k) \cdot [l_1(k) + l_2(k)]; \\ c_{32}(k) &= v_1(k) \cdot \bar{r}_2(k) \cdot [l_1(k) + \bar{c}_2(k)]; & c_{42}(k) &= v_1(k) \cdot \bar{v}_2(k) \cdot [l_1(k) + \bar{l}_2(k)]; \\ c_{33}(k) &= \bar{v}_1(k) \cdot r_2(k) \cdot [\bar{l}_1(k) + c_2(k)]; & c_{43}(k) &= \bar{v}_1(k) \cdot v_2(k) \cdot [\bar{l}_1(k) + l_2(k)]; \\ c_{34}(k) &= \bar{v}_1(k) \cdot \bar{r}_2(k) \cdot [\bar{l}_1(k) + \bar{c}_2(k)]; & c_{44}(k) &= \bar{v}_1(k) \cdot \bar{v}_2(k) \cdot [\bar{l}_1(k) + \bar{l}_2(k)]. \end{aligned}$$

from every possible state, mathematical expectations of transition values of hybrid vehicles at filling and charging stations are determined according to a matrix of transition values in the form of:

$$\begin{aligned} M_{S_1}(k) &= c_{11}(k) + c_{12}(k) + c_{13}(k) + c_{14}(k); \\ M_{S_2}(k) &= c_{21}(k) + c_{22}(k) + c_{23}(k) + c_{24}(k); \\ M_{S_3}(k) &= c_{31}(k) + c_{32}(k) + c_{33}(k) + c_{34}(k); \\ M_{S_4}(k) &= c_{41}(k) + c_{42}(k) + c_{43}(k) + c_{44}(k), \end{aligned} \quad (19)$$

or in the equivalent record using mathematical expectations concerning recovery and conservation of both mechanical and electrical subsystems,

$$\begin{aligned} M_{S_1}(k) &= M_{C_1}(k) + M_{C_2}(k); \\ M_{S_2}(k) &= M_{C_1}(k) + M_{L_2}(k); \\ M_{S_3}(k) &= M_{L_1}(k) + M_{C_2}(k); \\ M_{S_4}(k) &= M_{L_1}(k) + M_{L_2}(k). \end{aligned} \quad (20)$$

The obtained mathematical expectations of transition values for every possible state form the row matrix:

$$M_{(1,4)}(k) = \left\| M_{S_1}(k) \quad M_{S_2}(k) \quad M_{S_3}(k) \quad M_{S_4}(k) \right\|. \quad (21)$$

Within each pitch, corresponding probabilities of hybrid vehicles states are assumed as those determined with the help of a matrix of transition probabilities $P_{(4,4)}(k)$ in the form of column matrix $P_{(4,1)}(k)$. The product of row matrix $M_{(1,4)}(k)$ of mathematical expectations of transition values possible state by column matrix $P_{(4,1)}(k)$ of the probabilities of the states determines the expected value of random process of hybrid vehicles transition according to the possible states:

$$M(k) = M_{(1,4)}(k) \cdot P_{(4,1)}(k). \quad (22)$$

Total cost of random Markov process of recovery-conservation of hybrid vehicles at a filling and charging station during a day is estimated as follows:

$$\sum_k M(k) \cdot \Delta t(k). \quad (23)$$

Summary. Method to estimate economic efficiency of filling and charging stations for hybrid vehicles is proposed on the basis of the theory of Markov random processes. Dynamic model of random process of hybrid vehicles maintenance at filling and charging station in the form of asymmetric state graph with four peaks and sixteen arches is developed.

A method to estimate economic efficiency for a filling and charging station for hybrid vehicles maintenance is proposed. The method is based upon a theory of Markov random processes. A dynamic model of random process of hybrid vehicles maintenance at a filling and charging station is developed in the form of asymmetric state graph with four peaks and sixteen arches. Adequate mathematical model of Markov random process for the maintenance of hybrid vehicles is developed in the form of recurrent matrix form of 4th order. Values for recovery and conservation of both mechanical and electrical subsystems of hybrid vehicles are considered as discrete random values; corresponding distribution laws are determined. Matrices of transition values, mathematical expectations of values of certain transitions as well as mathematical expectations of a random Markov process on the whole are introduced to estimate economic efficiency of a filling and charging station for hybrid vehicles.

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