Propulsion System Design of Electric and Hybrid Vehicles

Mehrdad Ehsani, *Fellow, IEEE,* Khwaja M. Rahman, *Student Member, IEEE,* and Hamid A. Toliyat, *Member, IEEE*

***Abstract*—There is a growing interest in electric and hybrid-electric vehicles due to environmental concerns. Recent efforts are directed toward developing an improved propulsion system for electric and hybrid-electric vehicles applications. This paper is aimed at developing the system design philosophies of electric and hybrid vehicle propulsion systems. The vehicles' dynamics are studied in an attempt to find an optimal torque-speed profile for the electric propulsion system. This study reveals that the vehicles' operational constraints, such as initial acceleration and grade, can be met with minimum power rating if the power train can be operated mostly in the constant power region. Several examples are presented to demonstrate the importance of the constant power operation. Operation of several candidate motors in the constant power region are also examined. Their behaviors are compared and conclusions are made.**

***Index Terms*—Electric vehicle, hybrid electric vehicle, motor drives, road vehicle electric propulsion, road vehicle propulsion.**

I. Introduction

THE CONCEPT of the electric vehicle (EV) was conceived in the middle of the previous century. After the introduction of the internal combustion engine (ICE), EV's remained in existence side by side with the ICE for several years. The energy density of gasoline is far more than what the electrochemical battery could offer. Despite this fact, the EV continued to exist, especially in urban areas due to its self-starting capability. However, soon after the introduction of the electric starter for ICE's early this century, despite being energy-efficient and nonpolluting, the EV lost the battle completely to the ICE due to its limited range and inferior performance. Since then, the ICE has evolved, improved in design, and received widespread acceptance and respect. Although this essentially is the case, EV interest never perished completely and whenever there has been any crisis regarding the operation of ICE automobiles, we have seen a renewed interest in the EV. The early air quality concerns in the 1960's and the energy crisis in the 1970's have brought EV's back to the street again. However, the most recent environmental awareness and energy concerns have imposed, for the first time since its introduction, a serious threat to the use of ICE automobiles.

The ICE automobile at the present is a major source of urban pollution. According to figures released by the U.S. Environmental Protection Agency (EPA), conventional ICE vehicles currently contribute 40%–50% of ozone, 80%–90% of carbon monoxide, and 50%–60% of air toxins found in urban areas [1]. Besides air pollution, the other main objection regarding ICE automobiles is their extremely low efficiency use of fossil fuel. Hence, the problem associated with ICE automobiles is threefold: environmental, economical, as well as political. These concerns have forced governments all over the world to consider alternative vehicle concepts. The California Air Resource Board (CARB) is among the few that acted first through the declaration of the Clear Air Act of September 1990. This act requires that 52% of all vehicles sold in that state be either low-emission vehicles (LEV's)—48%, ultralow-emission vehicles (ULEV's)—2%, or zero-emission vehicles (ZEV's)—2%, by 1998 [2]. Similar measures are being considered in other states and nations as well.

EV's and hybrid-electric vehicles (HEV's) offer the most promising solutions to reduce vehicular emissions. EV's constitute the only commonly known group of automobiles that qualify as ZEV's. These vehicles use an electric motor for propulsion and batteries as electrical-energy storage devices. Although there have been significant advancements in motors, power electronics, microelectronics, and microprocessor control of motor drives, the advancement in battery technology has been relatively sluggish. Hence, the handicap of short range associated with EV's still remains. Given these technology limitations, the HEV seems to be the viable alternative to the ICE automobile at the present. HEV's qualify as ULEV's and do not suffer from the range limitations imposed by EV's. These vehicles combine more than one energy source to propel the automobile. In heat engine/battery hybrid systems, the mechanical power available from the heat engine is combined with the electrical energy stored in a battery to propel the vehicle. These systems also require an electric drivetrain to convert electrical energy into mechanical energy, just like the EV. Hybrid-electric systems can be broadly classified as series or parallel hybrid systems [3].

In series hybrid systems, all the torque required to propel the vehicle is provided by an electric motor. On the other hand, in parallel hybrid systems the torque obtained from the heat engine is mechanically coupled to the torque produced by an electric motor [3]. In the EV, the electric motor behaves exactly in the same manner as in a series hybrid. Therefore, the torque and power requirements of the electric motor are roughly equal for an EV and series hybrid, while they are lower for a parallel hybrid.

Manuscript received February 26, 1996; revised April 17, 1996.

The authors are with the Texas Applied Power Electronics Center, Department of Electrical Engineering, Texas A&M University, College Station, TX 77843-3128 USA.

Publisher Item Identifier S 0278-0046(97)00069-5.

This paper presents the EV and HEV propulsion system design philosophies. The paper is organized as follows. Section II describes the design constraints and the variables for EV and HEV systems. Design philosophies of EV and HEV propulsion systems are presented in Sections III and IV, respectively. Section V examines several of the most commonly used motors for EV and HEV system design. Section VI presents some test data from the Texas A&M University, College Station, hybrid vehicle. Summary and conclusions are presented in Section VII.

II. SPECIFICATIONS OF EV AND HEV PROPULSION SYSTEM DESIGN

A. System Design Constraints

Vehicle operation consists of three main segments. These are: 1) the initial acceleration; 2) cruising at vehicle rated speed; and 3) cruising at the maximum speed. These three operations provide the basic design constraints for the EV and HEV drivetrain. A drivetrain capable of meeting these constraints will function adequately in the other operational regimes. Refinements to these basic design constraints are necessary for an actual commercial product, but those are beyond the scope of this paper. The objective here is to meet these constraints with minimum power. The variables defining the above design constraints are:

1) vehicle rated velocity, v_{rv};
2) specified time to attain this velocity, t_f;
3) vehicle maximum velocity, $v_{\max}$;
4) vehicle mass and other physical dimensions.

1) Initial Acceleration: The initial acceleration force takes the vehicle from standstill to its rated velocity, v_{rv}, in some specified time, t_f seconds. This force is supplied entirely by the electric power train in an EV or series HEV. In a parallel HEV, the acceleration force is supplied by the electric power train in combination with the ICE power train.

2) Cruising at Rated Vehicle Speed v_{rv}: The electric motor provides the necessary propulsion force at rated vehicle speed in the EV and series HEV. On the other hand, the ICE of the parallel HEV should be capable of delivering enough force, without any help from the electric power train, to overcome road load and cruise at the rated vehicle speed on a grade of at least 3%. In addition, there should be a margin of about 10% power to charge the batterypack.

3) Cruising at Maximum Vehicle Speed: The maximum cruising force is provided by the electric motor in the EV and series HEV. In the parallel HEV, the electric motor and ICE should work in combination to provide the required force to sustain the vehicle at its maximum velocity.

B. System Design Variables

The main component of the EV is its electrical power train. However, in the HEV the propulsion system is a combination of the electric motor and ICE. The electric propulsion design

1) electric motor power rating;
2) motor rated speed;
3) motor maximum speed;
4) the extent of constant power speed range beyond the rated speed;
5) gear ratio between motor shaft and the wheel shaft (transmission).

Designing an optimal torque-speed profile for the ICE is beyond the scope of this paper. However, assuming a typical ICE torque-speed profile, we will specify the required ICE power by our design procedure. Therefore, the design variables for the mechanical propulsion system are:

1) ICE size;
2) gear ratio between ICE and the wheel shaft.

As mentioned earlier, the main design objective is to find the minimum drive weight, volume, and cost that will meet the design constraints with minimum power. EV system design is addressed first. The HEV system design is then presented as a modification of the EV system design.

C. Road Load Characteristics

The road load (F_w) consists of rolling resistance (f_{ro}), aerodynamic drag (f_l), and climbing resistance (f_{st}) [4]:

$$F_w = f_{ro} + f_l + f_{st}. \tag{1}$$

The rolling resistance (f_{ro}) is caused by the tire deformation on the road:

$$f_{ro} = f \cdot m \cdot g \tag{2}$$

where f is the tire rolling resistance coefficient. It increases with vehicle velocity and also during vehicle turning maneuvers. Vehicle mass is represented by m, and g is the gravitational acceleration constant.

Aerodynamic drag, f_l, is the viscous resistance of air acting upon the vehicle:

$$f_l = 0.5\xi C_W A(v + v_0)^2 \tag{3}$$

where ξ is the air density, C_W is the aerodynamic drag coefficient, A is the vehicle frontal area, v is the vehicle speed, and v_0 is the head-wind velocity.

The climbing resistance (f_{st} with positive operational sign) and the downgrade force (f_{st} with negative operational sign) is given by

$$f_{st} = m \cdot g \cdot \sin\alpha \tag{4}$$

where α is the grade angle.

A typical road load characteristic as a function of vehicle speed is shown in Fig. 1. The following assumptions are made in the plot:

1) velocity independent rolling resistance;
2) zero head-wind velocity;

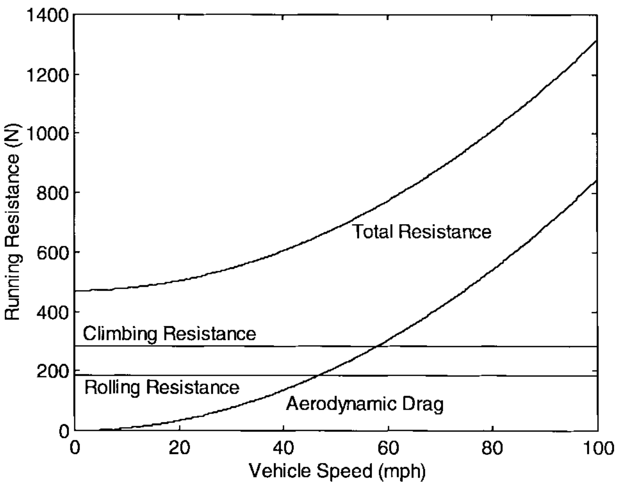

Fig. 1. Typical road load characteristics as a function of vehicle speed.

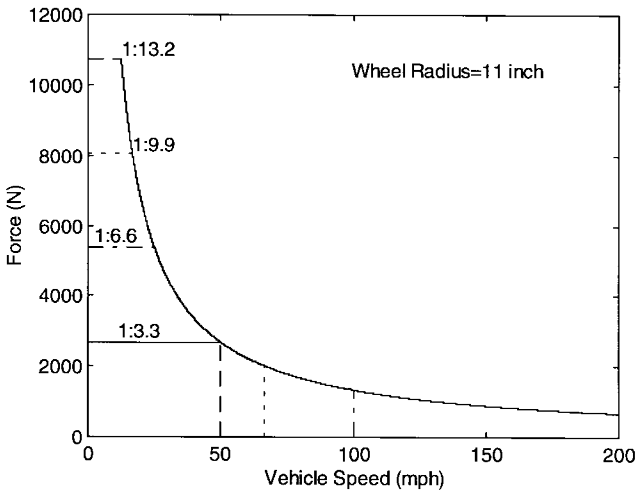

Fig. 2. Torque-speed diagram of an electrical motor in terms of tractive force and vehicular speed with gear size as the parameter.

These assumptions will be used in the analysis presented in the following sections, unless otherwise specified. These assumptions do not change the general trend of the solution and can be easily relaxed.

The motive force F available from the propulsion system is partially consumed in overcoming the road load, F_W. The net force, $F - F_W$, accelerates the vehicle (or decelerates when F_W exceeds F). The acceleration is given by

$$a = \frac{F - F_W}{k_m \cdot m} \tag{5}$$

where k_m is the rotational inertia coefficient to compensate for the apparent increase in the vehicle's mass due to the onboard rotating mass.

III. EV System Design

The main component of the EV drivetrain is its electric motor. The electric motor in its normal mode of operation can provide constant-rated torque up to its base or rated speed. At this speed, the motor reaches its rated power limit. The operation beyond the base speed up to the maximum speed is limited to this constant power region. The range of the constant power operation depends primarily on the particular motor type and its control strategy. However, some electric motors digress from the constant power operation, beyond certain speed, and enter the natural mode before reaching the maximum speed. The maximum available torque in the natural mode of operation decreases inversely with the square of the speed. This range of operation is neglected in the analysis presented in this section, unless otherwise specified. It is assumed that the electric motor operates in the constant power region beyond the base speed and up to the maximum speed. Nevertheless, for some extremely high-speed motors the natural mode of operation is an appreciable part of its total torque-speed profile. Inclusion of this natural mode for such motors may result in a reduction of the total power requirement. Of course, power electronic controls allow the motor to operate at any point in the torque-speed plane, below

is the profile of this envelope that is important in the motor drive selection and design.

In order to free up the motor speed from the vehicle speed, for design optimization, gearing between the motor shaft and the drive shaft is required. In our design, we will make the following assumptions.

1) Single gear ratio transmission operation—power electronic control allows instantaneous matching of the available motor torque with the required vehicle torque, at any speed; therefore, multiple gearing in order to match the motor torque-speed to the vehicle torque-speed is no longer a necessity;
2) Ideal loss free gear—without loss of generality, the gear losses can be incorporated at the end of analysis.

The gear ratio and size will depend on the maximum motor speed, maximum vehicle speed, and the wheel radius. Higher maximum motor speed, relative to vehicle speed, means a higher gear ratio and a larger gear size. The selection criterion for the maximum motor speed will be further discussed later. The torque-speed diagram of a typical motor is drawn in Fig. 2, but in terms of tractive force and vehicular speed for different gear ratios. Notice the electric motor base speed and maximum speed, in terms of the vehicle speed, depend on the gear ratio. A design methodology based on the three regions of operation will now be presented.

A. Initial Acceleration

The force-velocity profile of a typical motor is redrawn in Fig. 3. In this figure, v_{rm} is the electric motor rated speed, v_{rv} is the vehicle rated speed, and $v_{\max}$ is the vehicle maximum speed. The motor maximum speed must correspond to this $v_{\max}$, after the gear ratio transformation. The figure also shows (the dashed curve) the force-velocity profile of the motor in the natural mode. This mode of operation, however, is neglected unless otherwise specified.

The range of operation for initial acceleration is 0–v For

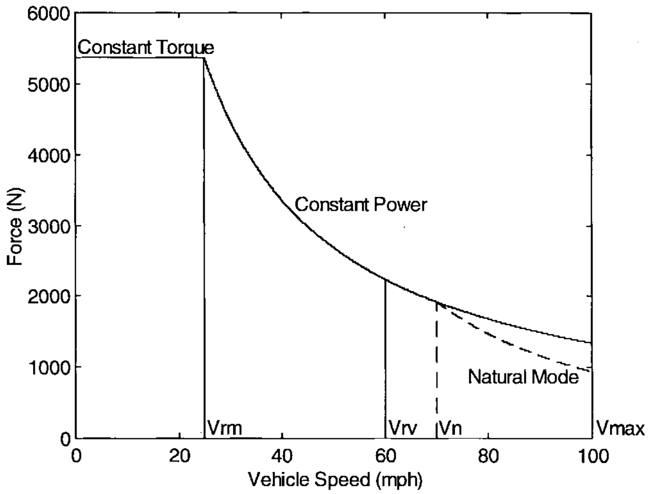

Fig. 3. Typical torque-speed profile of electric motor in terms of tractive force and vehicular speed.

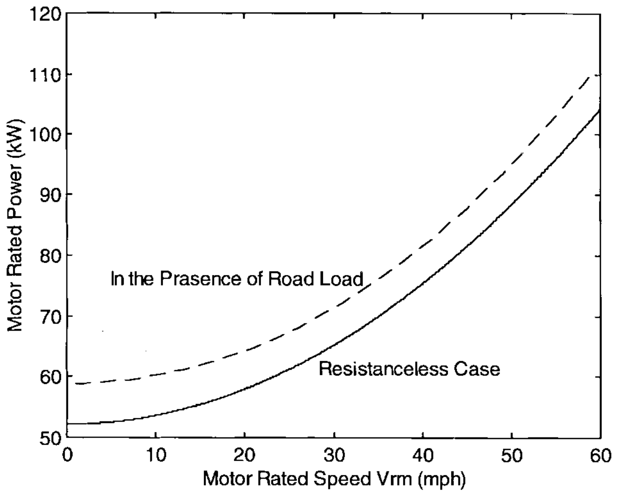

Fig. 4. Acceleration power requirement as a function of motor rated speed. Continuous curve—resistanceless case, dashed curve—in the presence of road load.

maximum acceleration, the motor operates in constant rated force (torque), $F_{v\text{rated}} = P_m/v_{rm}$, up to the motor rated speed, v_{rm}, and in constant power, $F_v = P_m/v$, at speeds beyond the base speed, up to the vehicle rated speed, v_{rv}. Here, P_m is the motor rated power. We assume $v_{rv} > v_{rm}$. The wisdom of this assumption will become clear shortly. The differential equation describing the performance of the system is given by (5) and is repeated here for convenience:

$$a = \frac{dv}{dt} = \frac{F - F_W}{k_m \cdot m}$$

F is the motive force available from the propulsion system and F_W is the running resistance (road load). The boundary conditions are:

at $t = 0$, vehicle velocity $v = 0$.
at $t = t_f$, vehicle velocity $v = v_{rv}$.

To gain insight, we will solve (5) under the most simplifying assumptions.

1) The vehicle is on a level ground.
2) The rolling resistance is zero.
3) Aerodynamic drag is zero.

These assumptions will be relaxed later for a more realistic solution. The above assumptions will result in a closed-form solution for the motor rated power P_m. The insight gained from the closed-form solution is also valid for the more practical design involving running resistances.

With these simplifying assumptions, the governing differential equation reduces to

$$a = \frac{dv}{dt} = \frac{F}{m} \quad (\text{assuming } k_m = 1)\,.$$

This differential equation is solved with the previous boundary conditions and the force-speed profile of Fig. 3. The differential equation is integrated within the acceleration interval of 0 to v_{rv} in 0 to t_f s, in order to get a closed-form solution for the rated power P_m:

$$\int^{v_{rv}} dv \qquad \int^{t_f} \qquad (6)$$

The left-hand side integral is broken into two parts: the 0–v_{rm} constant force operation and the v_{rm}–v_{rv} constant power operation:

$$m \int_0^{v_{rm}} \frac{dv}{\frac{P_m}{v_{rm}}} + m \int_{v_{rm}}^{v_{rv}} \frac{dv}{\frac{P_m}{v}} = t_f. \qquad (7)$$

Now solving for P_m, we get

$$P_m = \frac{m}{2t_f}\left(v_{rm}^2 + v_{rv}^2\right). \qquad (8)$$

For minimum motor power, differentiating P_m with respect to v_{rm} and setting it to zero gives

$$v_{rm} = 0. \qquad (9)$$

This establishes a theoretical limit for minimum motor power. For $v_{rm} = 0$, the electric motor operates entirely in the constant power region. Therefore, if the motor is performing 0–v_{rv} in t_f seconds in constant power alone, the power requirement is minimum. On the other hand, if the motor operates in the constant torque (force) region during the entire 0 to t_f period, we will have $v_{rm} = v_{rv}$. In this case, (8) shows that the power requirement is twice that of constant power operation. The solid line curve of Fig. 4 shows an example of the motor power requirements between these two extremes. Of course, entire operation in constant power regime is not practically realizable. However, this theoretical discussion demonstrates that longer constant power range of operation will lower the motor power.

Having discussed the simplified resistanceless case, we now solve the more realistic case involving the running resistance. The vehicle differential (5) can be solved under the same boundary conditions as before with the presence of the running resistance F_W. In this case, a closed-form solution is feasible. However, the result is a transcendental equation involving rated motor power P_m, rated motor velocity v_{rm}, rated vehicle velocity v_{rv}, acceleration time t_f, and all the other system aerodynamic drag coefficient C_W, etc. The resulting equation can be solved numerically for P_m for a specific motor rated velocity v_{rm}, using any standard root-seeking method such as the secant method [5].

Let us assume that it is desired to obtain P_m for the following case:

- 0–26.82 m/s (0–60 mi/h) in 10 s;
- vehicle mass of 1450 kg;
- rolling resistance coefficient of 0.013;
- aerodynamic drag coefficient of 0.29;
- wheel radius of 0.2794 m (11 in);
- level ground;
- zero head-wind velocity.

A plot of the resulting motor rated power versus motor rated speed, in terms of vehicle speed, is shown in Fig. 4 (the dashed curve).

Examination of Fig. 4 (the dashed curve) results in the following conclusions:

1) rated power versus v_{rm} curve shows the same general trend of the resistanceless case;
2) rated motor power requirement is minimum for continuous constant power operation $v_{rm} = 0$;
3) rated motor power is roughly twice that of continuous constant power operation for constant force (torque) operation $v_{rv} = v_{rm}$;
4) rated motor power remains close to its minimum up to about 20 mi/h of rated motor speed and then grows rapidly.

B. *Cruising at Rated Vehicle Velocity*

A power train capable of accelerating the vehicle to the rated velocity, v_{rv}, will always have sufficient cruising power at this speed. Hence, the constraint of cruising at rated vehicle speed is automatically met for the case of the EV. Of course, cruising range is another issue related to the battery design which is outside the scope of this paper. However, minimizing the power of the drive will help the battery size.

C. *Cruising at Maximum Vehicle Velocity*

The power requirement to cruise at maximum vehicle speed can be obtained as

$$P_{v\max} = (f_{ro} + f_{st}) \cdot v_{\max} + f_l(v) \cdot v_{\max}. \qquad (10)$$

Since aerodynamic drag dominates at high speeds, this power requirement increases with the cube of maximum vehicle velocity. If this vehicle power requirement is greater than the motor power calculated previously $(P_{v\max} > P_m)$, then $P_{v\max}$ will define the motor power rating. However, in general, P_m will dominate $P_{v\max}$, since modern vehicles are required to exhibit a high-acceleration performance. As mentioned before, some extremely high-speed motors usually have three distinct modes of operation. The initial constant torque operation, followed by a range of constant power operation, then to the maximum speed in natural mode (see the entire constant power range for initial acceleration of the vehicle. The operation beyond that would be in the natural mode. This would allow a longer constant power operation in the initial acceleration. Consequently, the motor power requirement will be lower. This scheme will work provided the motor has adequate torque in natural mode to meet the constraints at the maximum vehicle speed. Otherwise, some part of the constant power operation has to be used for the vehicle operation beyond the rated vehicle speed.

TABLE I
EV POWER REQUIREMENT AS A FUNCTION OF CONSTANT POWER RANGE

	Extended Constant HP Speed Range					
	1:1	1:2	1:3	1:4	1:5	1:6
Motor Rated Power (KW)	110	95	74	67	64	62

Natural mode of motor operation is not the preferred mode beyond the rated vehicle speed. Unfortunately, no control algorithm presently exists to operate some high-speed motors entirely in constant power beyond their base speed. However, the natural mode, if included, can lower the overall power requirement. The speed at which the electric motor can enter the natural mode and still meet the power requirement at maximum vehicle speed is obtained from

$$v_n = v_{\max} \sqrt{\frac{P_{v\max}}{P_m}}. \qquad (11)$$

Note that the initial acceleration power is also a function of v_n (extended constant power range). Hence, v_n and P_m have to be solved iteratively. Also, the gear ratio between the drive shaft and the motor shaft is to be determined by matching v_n with the motor speed at which it enters the natural mode. More discussion about the natural mode of operation appears in Section VI. The rest of the analysis is done assuming constant power operation beyond the base speed up to the maximum speed.

The importance of extending the constant power speed range can be better understood by comparing the required motor power for different constant power speed ranges (as a multiple of its base speed). Table I shows an example of power requirement for several constant power ranges for the following case:

1) maximum motor speed is 10 000 r/m;
2) maximum vehicle speed is 44.7 m/s (100 mi/h);
3) other system variables and constants are the same as the previous example.

Here, the required gear ratio to match the maximum motor speed to the maximum vehicle speed for a wheel radius of 0.2794 m (11 in) is 1:6.55. The results of Table I suggest an extended range of 4–6 times the base motor speed in order to significantly lower the motor power requirement.

Finally, we examine the effect of maximum motor speed and the extended constant power range on the overall system performance. In the context of EV/HEV design, we classify motors with maximum speeds of less than 6000 r/m as low-speed motors, those with speeds of 6000–10 000 r/m as

DOCKET ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.