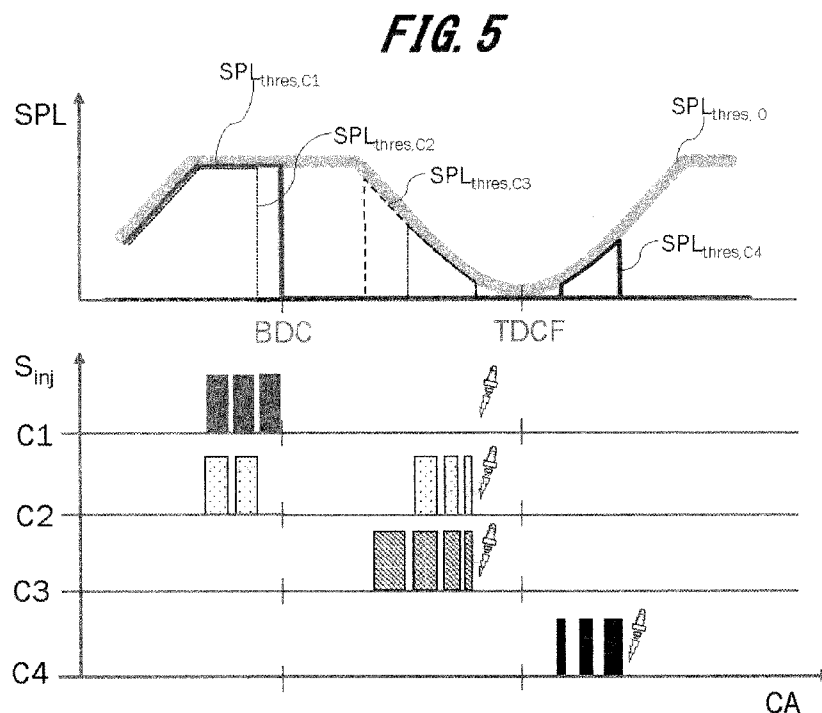




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(54) Title: METHOD AND DEVICE FOR CONTROLLING THE FUEL INJECTION OF AN INTERNAL COMBUSTION ENGINE



(57) Abstract: The present subject-matter relates to a method and a control device for reducing unburned hydrocarbons and particle emissions of an internal combustion engine especially in cold engine conditions. The problem to be solved is to provide automatic generation of an injection profile that considers the requirements of different combustion modes in various operation points of an internal combustion engine. This is achieved by controlling the fuel injection by means of an injection profile comprising multiple fuel injections. The profile is generated by setting an injection signal to a positive value at predetermined time points of the injection cycle in which a calculated spray penetration length is smaller than or equal to a spray penetration length threshold, and resetting the injection signal to zero at predetermined time points of the injection cycle in which the calculated spray penetration length exceeds the spray penetration length threshold until a fuel amount calculated on the basis of the previously generated fuel injection profile exceeds

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a predetermined fuel amount.

Description

Title of Invention: METHOD AND DEVICE FOR CONTROLLING THE FUEL INJECTION OF AN INTERNAL COMBUSTION ENGINE

Technical Field

[0001] The present subject-matter relates to a method and a control device for controlling a fuel injection of an internal combustion engine, preferably a spark ignited combustion engine, by means of an injection profile comprising multiple fuel injections, which is generated depending on a calculated spray penetration length of the fuel to be injected.

Background Art

[0002] The coming stringent legal requirements necessitate a further reduction in emissions from internal combustion engines, especially in the cold-start phase. This requires both a reduction in raw emissions and early operational readiness of the catalyst. Rapid heating of the catalyst requires late ignition timing and injection of a small amount of fuel just before ignition. For reducing the raw emissions, in particular hydrocarbon and particle emissions, at the same time, it is mandatory to avoid wall wetting in the combustion chamber. This is not only required in the cold start phase but is a general requirement for fuel injection. Multiple fuel injection is known as important measure to deal with the above-described challenges. However, to define the optimal injection profile in different environmental circumstances requires a high calibration effort. Thus, there is a need for automatically determine the injection timing of multiple injections in connection with different combustion modes used in the entire engine map.

Citation List

Patent Literature

[0003] Patent Literature 1: US 7770813 B2

Summary of Invention

Technical Problem

[0004] Patent Literature 1 describes a method for reducing the spray penetration using multiple injections and providing a dwell time between the successive injection events that allows each successive injection event to be independent of other successive events so that the overall spray penetration of the total injection event is reduced relative to that of a single fluid injection event.

[0005] However, the teaching of Patent Literature 1 does neither provide automatic generation of the injection profile nor does it take into account different combustion modes that require the injection timing to be aligned with the ignition timing.

An object of the described subject matter is to provide a model-based generation of an injection profile that considers the requirements of different combustion modes in various operation points of an internal combustion engine.

Solution to Problem

[0006] The above-described object is solved by the subject matter according to the independent claims. Further preferred developments are described by the dependent claims.

[0007] The claimed subject matter comprises a method for controlling a fuel injection of an internal combustion engine (hereinafter also shortly “engine”). Preferably, the engine may be a spark ignited engine. Most preferably the engine may be a spark ignited engine having a direct fuel injection.

[0008] The internal combustion engine comprises at least one cylinder, in which a combustion chamber is formed by a cylinder wall, a cylinder head and a top of a piston. The piston moves reciprocally in the cylinder driven by a crankshaft. The piston may be connected to the crankshaft via a connecting rod. Preferably, the piston may move by the piston stroke s from a bottom dead center (BTC) to a top dead center (TDC). The crank angle-dependent piston stroke s can be determined with the following formula, wherein j denotes the crank angle, r denotes the stroke length of the crank shaft and l_s denotes the rod ratio:

[0009] [Math.1]

$$s(\varphi) = r \cdot \left[(1 - \cos\varphi) + \frac{1}{l_s} \left(1 - \sqrt{1 - \lambda_s^2 \cdot \sin^2\varphi} \right) \right] \quad \text{Formula (1).}$$

[0010] The engine further comprises at least one fuel injector which is configured to inject fuel into the combustion chamber. Preferably, the at least one fuel injector may be a high-pressure injector configured to inject fuel directly in the combustion chamber. The high-pressure injector may be driven by a solenoid valve or a piezo element.

[0011] Furthermore, the engine comprises at least one control device which is configured to control the fuel injection. Preferably the control device may be the engine control unit (ECU). The control device may be integrated into the internal combustion engine or, alternatively, it may be disposed at a position within the vehicle remote to the combustion engine, and the control device and the engine may be connected via one or more signal lines. The control device may be the engine control device (ECU) or one or more separate control devices.

According to the claimed subject matter, the fuel injection is controlled by comparing a calculated spray penetration length of fuel to be injected into the combustion chamber with a spray penetration length threshold at predetermined time points of an injection cycle.

- [0012] In order to avoid wall and piston wetting in the combustion chamber the spray penetration length of the fuel to be injected has to be shorter than the distance between the spray hole and the cylinder wall and the distance between the spray hole and the piston. The distance of the spray jets from the cylinder wall is taken into account when selecting an injector for a particular engine by performing a so-called spray targeting, which illustrates the location of the spray jets in the combustion chamber. Thus, the required threshold value for the penetration length of the spray jet can be reduced to the distance between the spray opening and the top of the piston as described below.
- [0013] The spray penetration length of the fuel to be injected may depend on several parameters. The most important parameters may be the fuel pressure and the pressure and temperature in the combustion chamber. These parameters may be considered in the physical model for calculating the spray penetration length described below.
- [0014] According to the claimed method, the first predetermined time point for performing the comparison is an end of the injection cycle. The term "injection cycle" shall be understood as the area(s) of the engine working cycle in which injection should take place to generate torque and to fulfill the requirements of the predetermined combustion mode. A complete injection cycle, which may be independent of the combustion mode, may start shortly after closing of the exhaust valves and end just before ignition timing. However, depending on the combustion mode, the injection cycle may vary, e.g., in homogenous combustion mode, the injection cycle may end before the end of the intake stroke, to achieve a homogenous cylinder charge. This means that in homogenous combustion mode the end of the injection cycle may be, e.g., before Bottom Dead Center. In contrast, in stratified mode the last injection event may end, e.g., close before ignition timing. Starting the calculation at the end of the injection cycle considers the conditions of the different combustion modes, which require an alignment of the latest injection with the ignition.
- [0015] Based on the comparison of the calculated spray penetration length with the spray penetration length threshold, a fuel injection profile comprising multiple fuel injections is generated. This is done by setting an injection signal to a positive value at the predetermined time points of the injection cycle in which the calculated spray penetration length is smaller than or equal to the spray penetration length threshold, and resetting the injection signal to zero at the predetermined time points of the injection cycle in which the calculated spray penetration length exceeds the spray penetration length threshold. In other words, the injection timing and duration of multiple injections may be generated by allowing an injection only if the spray penetration length is below or equal to the spray penetration length threshold which represents the maximum allowable spray penetration length. By setting an injection signal to an arbitrary positive value, e.g., to one, if a spray penetration length is allowable and resetting the

injection signal to zero, if a spray penetration length is not allowable, a signal to be output by the control device to the injector representing the fuel injection profile can be generated. In case the time between setting and resetting the injection signal is smaller than the minimum actuation time of the injector, the injection signal is set to zero in this range.

- [0016] The generation of the fuel injection profile is carried out until a fuel amount calculated on the basis of the previously generated fuel injection profile exceeds a predetermined fuel amount. The predetermined fuel amount may be the total amount of fuel needed to meet the torque and/or lambda control requirements. After finishing the generation of the fuel injection profile, it is sent to the injector for performing the injection.
- [0017] The claimed method automatically calculates the complete injection profile, i.e., the number of injections and the start and end time of each injection for the subsequent injection cycle. The calculation is executed in a backward manner starting from the end of an injection cycle and finalizing the calculation at the beginning of an injection event. This allows for adapting the multiple injections to different combustion modes so that emissions and fuel consumption can be optimized at the same time.

- [0018] According to an aspect, the spray penetration length threshold may be determined depending on a position of the piston and a predetermined combustion mode.

As explained above, the claimed method assumes an injector adapted to the combustion chamber, so that only the distance between the spray hole and the top of the piston has to be considered when determine the spray penetration length threshold. A geometric threshold value for the penetration length of the spray jet can be determined using the following formula:

- [0019] [Math.2]

$$SPL_{thres,0}(\varphi) = \frac{1}{\sin(\alpha)} \cdot d(\varphi) \quad \text{Formula (2).}$$

- [0020] In Formula (2) α denotes the angle between a center axis of a spray jet and the center axis of the cylinder and d denotes the distance between the spray hole of the injector and the top of the piston, which is dependent on the piston stroke s according to Formula (1) and, thus, dependent on the crank angle j :

- [0021] However, to additionally consider the requirements of different combustion modes, which are predetermined in the engine map, the spray penetration length threshold has to be adapted.

Predetermined combustion modes may be, e.g., a lean-burn combustion with a stratified cylinder charge, a lean-burn combustion with a mixture of homogenous and stratified cylinder charge and a homogenous combustion with a stoichiometric cylinder charge.

[0022] The principle of stratified charge operation is to deliver a mixture that is sufficiently rich for combustion in the vicinity of the spark plug, while the rest of the cylinder receives a very lean mixture. Stratified charge operation enables reduced fuel consumption when running at lower loads due to reduced pumping losses and overall lean combustion. To achieve stable ignition of the mixture near the spark plug, several injections are carried out during the compression stroke, with the last injection taking place just before ignition. This means that the spray penetration length threshold may be set to zero, e.g., during the intake stroke and during the first half of the compression stroke, to include the requirements of the combustion mode into the generation of the fuel injection profile.

[0023] To take advantage of lean combustion even at medium loads a lean burn combustion with a mixture of homogenous and stratified cylinder charge is used in this area of the engine map. To achieve a homogenous charge one or more injections are carried out during the intake stroke. The stratified mixture is then created by one or more further injections during the second half of the compression stroke until just before ignition. Thus, the spray penetration length threshold may be set to zero, e.g., during the first half of the compression stroke.

For homogenous combustion, no injection during the compression stroke is needed, so that the spray penetration length threshold may be set to zero, e.g., during the compression stroke.

[0024] According to an aspect, the spray penetration length of fuel to be injected may be calculated using a physical model, which considers all relevant influences, such as the fuel pressure and the pressure and temperature in the combustion chamber. The model is represented by the following formula, in which k denotes a calibration parameter depending on pressure p_{cyl} , temperature T_{cyl} and gas concentration x_{cyl} in the combustion chamber, Dp denotes the difference between the fuel pressure and the cylinder pressure, t denotes the time after start of injection and a , b denote weighting coefficients of the pressure difference Dp and the time t :

[0025] [Math.3]

$$SPL = k \cdot (\Delta p)^a \cdot t^b \quad \text{Formula (3)}$$

$$\text{with } k = f(p_{cyl}, T_{cyl}, x_{cyl}).$$

[0026] Using a physical model for determining the spray penetration length improves calculation robustness and extrapolation behavior compared to a map-based calibration.

[0027] According to an aspect, a start of an injection may be determined by a backward calculation at a time when the calculated spray penetration length exceeds the spray penetration length threshold. The period/distance between the start of the injection and the time, where the spray has achieved the spray penetration length threshold may be

identified by using a map, which may be previously calibrated via test data from injector spray experiments.

- [0028] According to an aspect, a time period of the fuel injection profile between a falling edge by resetting the injection signal to zero and a subsequent rising edge by setting the injection signal to the positive value may be longer than a predetermined time threshold. In other words, the distance between the end of one injection and the start of a subsequent injection may be longer than a predetermined time threshold. The predetermined time threshold may be the dwell time of the injector or, if necessary, an additional offset may be added to the dwell time to further increase or decrease the distance between two injection events.
- [0029] According to an aspect, the end of the injection cycle may be determined depending on the predetermined combustion mode in relation to an ignition timing of the internal combustion engine. As explained above the duration of an injection cycle within the meaning of the claimed subject matter may depend on the combustion mode. To ensure optimal ignitability and combustion stability, the end of the injection cycle may be further determined in relation to an ignition timing. This means that if the ignition timing shifts, the complete injection profile will automatically be shifted as well, to maintain a constant distance between the end of the last injection and the ignition.
- [0030] According to an aspect, the fuel injection profile is generated by a backward calculation beginning at the end of the injection cycle. A rising edge determined as the first may characterize an end of a last injection, and a falling edge determined as the last may characterize a start of a first injection. In other words, due to the backward calculation beginning at the end of the injection cycle, a first setting of the injection signal (a first rising edge) may represent the end of a last injection and a last falling edge of the injection signal may represent the start of the first injection. The last falling edge of the injection signal may be determined depending on the predetermined fuel amount as explained below.
- [0031] According to an aspect, the fuel amount/total quantity of fuel calculated on the basis of the previously generated fuel injection profile is determined each time the injection signal is reset. First, a fuel amount/quantity of fuel of an injection corresponding to a time period between a last falling edge and a previous rising edge of the fuel injection profile may be calculated using a physical hydraulic model. In other words, the fuel amount of the last injection whose injection duration is defined by the time between the last falling edge and the previous rising edge, may be calculated. Then the calculated fuel amount may be added to a sum of previously calculated fuel amounts until the sum of previously calculated fuel amounts exceeds the predetermined fuel amount.
- [0032] A physics-based model is used to calculate the mass flow rate (MFR) of each

injection event. The model may be represented by the following formula:

[0033] [Math.4]

$$MFR = C_d \cdot A \cdot \sqrt{2 \cdot \rho_f \cdot \Delta p} \quad \text{Formula (4)}$$

[0034] In Formula (4) C_d denotes the flow coefficient of the injector, A denotes the opening section of the injector, ρ_f denotes the fuel density and Δp denotes the difference between the fuel pressure and the cylinder pressure. By integrating the mass flow rate (MFR) over the previously determined injection duration the fuel amount of each injection can be calculated.

[0035] According to an aspect, the start of the first injection may be determined based on a difference between the fuel amount calculated on the basis of the previously generated fuel injection profile and the predetermined fuel amount.

[0036] As explained above the claimed method ensures that the total quantity of fuel (sum of all single injection events) satisfies a predetermined fuel amount required, e.g., from lambda or torque control. Therefore, the method checks the total quantity of fuel after each calculation step and stops the calculation in case the the predetermined fuel amount is achieved. In this way, only the earliest injection event is used for the adjustment/control of the predetermined fuel amount. This is beneficial because the earliest injection event has the largest distance from spark event and therefore does not cause a disturbance on the ignition behaviour.

[0037] According to an aspect, the predetermined time points of the injection cycle at which the fuel injection profile is determined are arranged at equidistant intervals with respect to a crankshaft angle of the internal combustion engine.

The equidistant intervals may be, e.g., 1°CA , 0.5°CA , 0.1°CA depending on computational resources and required calculation accuracy. In other words, the method is executed on a crank angle resolved calculation basis, which means that it is independent of the engine speed.

[0038] The claimed subject matter further includes a control device for an internal combustion engine, which is configured to perform the above-described method or aspects thereof, and an internal combustion engine, which comprises the control device. In this context “to comprise the control device” means that the control device may be integrated into the internal combustion engine or, alternatively, it may be disposed at a position within the vehicle remote to the combustion engine, and the control device and the engine may be connected via one or more signal lines.

[0039] Furthermore, the claimed subject matter includes a computer program product storable in a memory comprising instructions which, when carried out by a computer or a computing unit, cause the computer to perform the above- described method or aspects thereof, as well as a computer-readable [storage] medium comprising in-

structions which, when executed by a computer, cause the computer to carry out said method or aspects thereof.

[0040] Summarizing, the claimed subject-matter allows to reduce the emissions of an internal combustion engine and, at the same time, its calibration effort by performing multiple injection on the basis of a model-based automatically generated fuel injection profile. Furthermore, the requirements of different combustion modes for multiple injection are taken into account when generating the fuel injection profile.

Brief Description of Drawings

[0041] In the following the subject matter will be further explained based on at least one preferential example with reference to the attached exemplary and schematic drawings, wherein:

[Fig. 1] Figure 1 depicts schematically an example of a single cylinder spark ignited combustion engine;

[Fig. 2A] Figure 2A depict schematically a generation of an injection profile according to the claimed method;

[Fig. 2B] Figure 2B depict schematically a generation of an injection profile according to the claimed method;

[Fig. 2C] Figure 2C depict schematically a generation of an injection profile according to the claimed method;

[Fig. 2D] Figure 2D depict schematically a generation of an injection profile according to the claimed method;

[Fig. 2E] Figure 2E depict schematically a generation of an injection profile according to the claimed method;

[Fig. 2F] Figure 2F depict schematically a generation of an injection profile according to the claimed method;

[Fig. 3] Figures 3 depicts a flowchart describing exemplary the method steps of the claimed method;

[Fig. 4] Figures 4 depicts an example of an engine map;

[Fig. 5] Figures 5 depicts exemplary different spray length penetration thresholds depending on the respective combustion mode according to the claimed method;

[Fig. 6A] Figure 6A depict an example of achieved emission reduction using different injection profiles according to the claimed method.

[Fig. 6B] Figure 6B depict an example of achieved emission reduction using different injection profiles according to the claimed method.

Description of Embodiments

[0042] In Figure 1 an example of a spark ignited single cylinder combustion engine is schematically illustrated, to explain the background of the claimed subject matter. It is

clear to those skilled in the art that the claimed subject matter is not limited to a single cylinder engine, but can be applied to engines with any number of cylinders.

- [0043] The depicted single cylinder engine comprises a combustion chamber 1 which is formed by the cylinder wall 1a, the top of the piston 2 and a cylinder head (not depicted) in which the intake valve 3, the outlet valve 4, the fuel injector 5 and the spark plug 6 are arranged. The piston 2 may move in the cylinder by the piston stroke s from a bottom dead center BTC to a top dead center TDC.
- [0044] The fuel injector 5 and the spark plug 6 are electrically connected to the control device 7. The control device 7 may determine the fuel injection profile according to the claimed method and send it to the injector 5. Furthermore, the control device 7 may control the ignition timing of the spark plug 6. The control device 7 may be integrated into the internal combustion engine or, alternatively, it may be disposed at a position within a vehicle remote to the combustion engine, and the control device 7 and the engine may be connected via one or more signal lines. The control device 7 may be the engine control device (ECU) or one or more separate control devices.
- [0045] In Fig. 1 the piston is positioned at BDC. However, it can be derived from Fig. 1 that if the piston is positioned close to TDC, which is the case when the injection takes place near the ignition timing, only a small fuel penetration length is allowable in order to avoid piston wetting.
- [0046] The phenomenon of wall and piston wetting is schematically depicted in Fig. 2A in connection with the resulting spray penetration length threshold $SPL_{\text{thres},0}$. As long as the piston is situated near BDC, no piston wetting but wall wetting may occur, which can be prevented by an optimized spray targeting of the injector as explained above. As the piston approaches top dead center, the spray may initially impinge on the outside of the piston, and as the piston continues to approach top dead center, the impingement point may move toward the piston center. The described impingement of the fuel on the piston surface defines the geometric spray penetration length threshold $SPL_{\text{thres},0}$ expressed by Formula (2). The parameters of Formula (2) are depicted in Fig. 2B, which schematically shows an example of a combustion chamber 1 with a piston 2, a spark plug 6 and an injector 5. As visible in Fig. 2B, the maximum allowable spray penetration length $SPL_{\text{thres},0}$ depends on the angle α between a center axis of a spray jet 7 and the center axis of the cylinder and the distance d between the spray hole of the injector and the top of the piston, which is dependent on the piston stroke s .
- [0047] Fig. 2C shows an example of the comparison between the stepwise calculated spray penetration length SPL with the geometric spray calculation length threshold $SPL_{\text{thres},0}$ which leads to the spray penetration lengths of the multiple injections. The depicted example refers to a combustion mode with catalyst heating, in which the ignition timing takes places after the firing top dead center TDC_F . The calculation of the spray

penetration length SPL starts at ignition timing to determine the fuel injection profile of the late multiple injections needed to accelerate the catalyst heating.

[0048] Fig. 2D shows that the spray penetration length SPL calculated by the model according to Formula (3) matches very well with experimental results, wherein the unbroken line indicates the model data and the broken line indicates the experimental data. Further, based on Figure 2D, it can be shown as to how to determine the start of an injection via a backward calculation. First, the distance $\Delta\phi$ between the start of the hydraulic injection $\phi_{start,k}$ and the current position ϕ_{act} , where the spray has achieved a certain spray length SPL_k , is identified. The position ϕ_{act} is indicated by a vertical broken line in Figure 2D which intersects the x-axis at the position where the SPL curve has reached the value SPL_k . The start of the hydraulic injection $\phi_{start,k}$ is also indicated by a broken vertical line which crosses the x-axis at the position where the SPL curve starts to rise. The difference between the two positions is the distance $\Delta\phi$. For example, said distance $\Delta\phi$ may be identified by using a map, e.g. $\Delta\phi = \text{map}(SPL_k, RP, \text{etc.})$, which has been previously calibrated via test data from injector spray experiments. Then, the start of the injection can be calculated based on the knowledge of the current position ϕ_{actual} and the distance $\Delta\phi$, e.g. by subtracting the distance $\Delta\phi$ from the current position ϕ_{actual} , i.e. $\phi_{start,k} = \phi_{actual} - \Delta\phi$.

[0049] Fig. 2E schematically shows the timing and quantity of the late multiple injections resulting from the calculation of the allowable spray penetration length shown in Fig. 2C. A fuel injection profile is depicted that comprises six injections in the region around TDC in order to improve the catalyst heating. The fuel injection profile may be generated by setting the injection signal S_{inj} to a positive value at the predetermined time points of the injection cycle in which the calculated spray penetration length is smaller than or equal to the spray penetration length threshold, and resetting the injection signal to zero at the predetermined time points of the injection cycle in which the calculated spray penetration length exceeds the spray penetration length threshold. It can be derived from Fig. 2F that the mass fuel rate MFR calculated according to Formula (4) also agrees very well with experimental results.

[0050] Fig. 3 shows a flow chart that describes the process steps of the claimed method by way of example. In a first step S100 the spray penetration threshold SPL_{thres} may be determined according to Formula (2). Additionally, the combustion mode may be taken into account, as described below in combination with Fig. 5. In step S101 the injection counter k is set to zero so that the crank angle j at which the calculation may start is set to the latest possible crank angle j_{latest} , namely to the crank angle being the end of the injection cycle (S102). In case of the injection counter $k > 0$ the crank angle for determining the next injection may be set to a crank angle j whose distance from the current crank angle j_{act} corresponds to the dwell time of the injector. This ensures that

the component-related distance between two injections is maintained. It may be also possible to increase or decrease the crank angle between two subsequent injections. In step S104, the equidistant interval counter between calculation steps is set to $i = 1$, and in step S105, the spray penetration length is calculated at crank angle $j - 1$, i.e., at the crank angle before the current crank angle when the equidistant interval is set to 1°CA .

- [0051] If the calculated spray penetration length SPL_k is lower than the spray penetration length threshold $\text{SPL}_{\text{thres}}$, the injection signal S_{inj} is set to 1 (S106) and the method precedes via step S106 to the next crank for calculating the spray penetration length there.
- [0052] If the calculated spray penetration length SPL_k is equal to or higher than the spray penetration length threshold $\text{SPL}_{\text{thres}}$, the spray penetration length calculation is terminated for the current injection and the injection signal S_{inj} is set to 0 (S108). Subsequently the start of the current injection event is determined based on the calculated spray penetration length SPL_k . To calculate the start of the current injection event, a model is used to return the distance $\Delta\phi$ between the start of the hydraulic injection $\phi_{\text{start},k}$ and the current position ϕ_{act} where the spray has achieved a certain spray length SPL_k , which is preferably a predefined value or the like. The model that is used can be a map-based structure which is calibrated via test data from injector spray experiments. The hydraulic start of injection SOI_k can then be determined via the equation: $\phi_{\text{start},k} = \phi_{\text{actual}} - \Delta\phi$. (S109) which has been described also in connection with Figure 2D. Since the entire hydraulic spray duration is known, the fuel amount $Q_{\text{model},k}$ may then be calculated according to Formula (4) (S110) based on the injection duration, as previously explained. In case the calculated fuel amount $Q_{\text{model},k}$ is lower than a minimum fuel amount Q_{min} of the injector, no injection is generated, and the method precedes to the next crank angle via step S106.
- [0053] In case the calculated fuel amount $Q_{\text{model},k}$ is higher than the minimum fuel amount Q_{min} of the injector, the calculated fuel amount $Q_{\text{model},k}$ is added to the previously calculated fuel amounts, and it is checked whether the sum of the calculated fuel amounts is equal to or higher than the predetermined fuel amount Q_{total} .
- [0054] If the sum of the calculated fuel amounts is lower than the predetermined fuel amount Q_{total} , the method precedes to step S111 for calculating the next injection. Otherwise, the generation of the fuel injection profile is terminated.
- [0055] The claimed method exemplarily described in Fig. 3 enables the automatic generation of a complete fuel injection profile that can be injected in the subsequent injection cycle. The method performs a backward calculation and takes into account the requirements of the various combustion modes as well as the constraints imposed by the injector.
- [0056] In Fig. 4 the distribution of different combustion modes over the entire engine map is

shown. At low loads and speeds the stratified combustion mode C3 with an overall air-fuel ratio of $\lambda > 1$ may be performed to reduce fuel consumption. At medium loads and speeds, the so-called homogeneous-stratified combustion mode C2 can be carried out to extend the advantages of a lean mixture to higher loads and speeds. At high loads and speeds, however, the homogenous combustion mode C1 may be needed to achieve the required engine power.

[0057] Fig. 5 depicts an example of the required fuel injection profiles corresponding to the respective combustion modes C1 to C3 and the resulting spray penetration length threshold SPL. Each fuel injection profile may be generated by setting the injection signal S_{inj} to a positive value, e.g., to one, at time points of the injection cycle in which the calculated spray penetration length is smaller than or equal to the spray penetration length threshold, and resetting the injection signal to zero time points of the injection cycle in which the calculated spray penetration length exceeds the spray penetration length threshold. In addition to any of the combustion modes C1 to C3, catalyst heating mode C4 may be carried out after cold start of the engine, which must then be additionally taken into account when generating the fuel injection profile.

[0058] In the depicted example three injections during the intake stroke are performed when operating the engine in homogenous mode. The latest injection ends at BDC so that the spray penetration length threshold $SPL_{thres, C1}$ can be set to zero after BDC. In contrast, the depicted example shows two injections during the intake stroke and three injections during the compression stroke for the homogenous-stratified mode C2. The latest injection ends just before ignition timing, e.g., close before ignition timing, which means that the spray penetration length threshold $SPL_{thres, C2}$ can only be set to zero in the first half of the compression stroke. In terms of the stratified combustion mode C3 four injections are performed during the compression stroke, resulting in a spray penetration length threshold $SPL_{thres, C3}$ which can be set to zero during the intake stroke and at the beginning of the compression stroke. Regarding the catalyst heating mode, one or more injections are carried out after TDC just before the late ignition timing, e.g., close before ignition timing. This means that a separate fuel injection profile may be generated for catalyst heating which may be combined with one of the other fuel injection modes depending on the combustion mode selected.

[0059] By modifying the geometric spray penetration length threshold $SPL_{thres, 0}$ with regard to the different combustion modes it is possible to specifically consider the requirements of each combustion mode. Furthermore, the calculation effort can be strongly reduced by comparing the calculated spray penetration length SKL with the spray penetration length threshold SKL_{thres} only in regions of the engine working cycle in which a potential injection is expected.

[0060] Figs. 6A, 6B depict an example of achieved emission reduction using different

injection profiles according to the claimed method. In Fig. 6A the specific effective fuel consumption be, the nitrogen oxides NO_x, the hydrocarbons HC and the particle number for multiple injections comprising three and five injections are depicted compared to the values measured when using a single injection. Fig. 6B shows the timing and duration of the various injections, represented by the injection current. The single injection is carried out during the intake stroke and the three multiple injections are also performed during the intake stroke. The five very short multiple injections, on the other hand, are distributed between the intake and compression strokes, with three injections performed during the intake stroke and two injections performed during the compression stroke. The last of the five injections is carried out shortly before the ignition timing.

- [0061] One can derive from Fig. 6A that generating a fuel injection profile according to the claimed method helps to reduce the emissions without effecting the fuel consumption. In particular, the hydrocarbons HC and the particle number can be significantly reduced when performing multiple injection according to the claimed subject matter. While the nitrogen oxides NO_x are almost the same for three and five injections, respectively, the hydrocarbons HC and the particle number PN can be further reduced for five injections according to the injection profile shown in Fig. 6B.
- [0062] Again summarizing, the claimed subject-matter allows to reduce the emissions of an internal combustion engine and, at the same time, its calibration effort by performing multiple injection on the basis of a model-based automatically generated fuel injection profile. Furthermore, the requirements of current combustion processes for multiple injection are taken into account when generating the fuel injection profile, which helps to significantly reduce the calculation effort.
- [0063] As will be appreciated by one of skill in the art, the present disclosure, as described hereinabove and the accompanying figures, may be embodied as a method, an apparatus (including a device, machine, system, computer program product, and/or any other apparatus), or a combination of the foregoing.
- [0064] Accordingly, embodiments of the present disclosure may take the form of an entirely hardware embodiment, an entirely software embodiment (including firmware, resident software, micro-code, etc.), or an embodiment combining software and hardware aspects that may generally be referred to herein as a "system". Furthermore, embodiments of the present disclosure may take the form of a computer program product on a computer-readable medium having computer-executable program code embodied in the medium.
- [0065] It should be noted that arrows may be used in drawings to represent communication, transfer, or other activity involving two or more entities. Double-ended arrows generally indicate that activity may occur in both directions (e.g., a command/request

in one direction with a corresponding reply back in the other direction, or peer-to-peer communications initiated by either entity), although in some situations, activity may not necessarily occur in both directions.

- [0066] Single-ended arrows generally may indicate activity exclusively or predominantly in one direction, although it should be noted that, in certain situations, such directional activity actually may involve activities in both directions (e.g., a message from a sender to a receiver and an acknowledgement back from the receiver to the sender, or establishment of a connection prior to a transfer and termination of the connection following the transfer). Thus, the type of arrow used in a particular drawing to represent a particular activity is exemplary and should not be seen as limiting.
- [0067] Aspects are described hereinabove with reference to flowchart illustrations and/or block diagrams of methods and apparatuses, and with reference to a number of sample views of a graphical user interface generated by the methods and/or apparatuses. It will be understood that each block of the flowchart illustrations and/or block diagrams, and/or combinations of blocks in the flowchart illustrations and/or block diagrams, as well as the graphical user interface, can be implemented by computer-executable program code.
- [0068] The computer-executable program code may be provided to a processor of a general purpose computer, special purpose computer, or other programmable data processing apparatus to produce a particular machine, such that the program code, which executes via the processor of the computer or other programmable data processing apparatus, create means for implementing the functions/acts/outputs specified in the flowchart, block diagram block or blocks, figures, and/or written description.
- [0069] These computer-executable program code may also be stored in a computer-readable memory that can direct a computer or other programmable data processing apparatus to function in a particular manner, such that the program code stored in the computer readable memory produce an article of manufacture including instruction means which implement the function/act/output specified in the flowchart, block diagram block(s), figures, and/or written description.
- [0070] The computer-executable program code may also be loaded onto a computer or other programmable data processing apparatus to cause a series of operational steps to be performed on the computer or other programmable apparatus to produce a computer-implemented process such that the program code which executes on the computer or other programmable apparatus provides steps for implementing the functions/acts/outputs specified in the flowchart, block diagram block(s), figures, and/or written description. Alternatively, computer program implemented steps or acts may be combined with operator or human implemented steps or acts in order to carry out an embodiment.

- [0071] It should be noted that terms such as "server" and "processor" may be used herein to describe devices that may be used in certain embodiments and should not be construed to limit to any particular device type unless the context otherwise requires. Thus, a device may include, without limitation, a bridge, router, bridge-router (brouter), switch, node, server, computer, appliance, or other type of device. Such devices typically include one or more network interfaces for communicating over a communication network and a processor (e.g., a microprocessor with memory and other peripherals and/or application-specific hardware) configured accordingly to perform device functions.
- [0072] Communication networks generally may include public and/or private networks; may include local-area, wide-area, metropolitan-area, storage, and/or other types of networks; and may employ communication technologies including, but in no way limited to, analog technologies, digital technologies, optical technologies, wireless technologies (e.g., Bluetooth), networking technologies, and internetworking technologies.
- [0073] It should also be noted that devices may use communication protocols and messages (e.g., messages created, transmitted, received, stored, and/or processed by the device), and such messages may be conveyed by a communication network or medium.
- [0074] Unless the context otherwise requires, the present disclosure should not be construed as being limited to any particular communication message type, communication message format, or communication protocol. Thus, a communication message generally may include, without limitation, a frame, packet, datagram, user datagram, cell, or other type of communication message.
- [0075] Unless the context requires otherwise, references to specific communication protocols are exemplary, and it should be understood that alternative embodiments may, as appropriate, employ variations of such communication protocols (e.g., modifications or extensions of the protocol that may be made from time-to-time) or other protocols either known or developed in the future.
- [0076] It should also be noted that logic flows may be described herein to demonstrate various aspects and should not be construed to limit the disclosure to any particular logic flow or logic implementation. The described logic may be partitioned into different logic blocks (e.g., programs, modules, functions, or subroutines) without changing the overall results.
- [0077] Often times, logic elements may be added, modified, omitted, performed in a different order, or implemented using different logic constructs (e.g., logic gates, looping primitives, conditional logic, and other logic constructs) without changing the overall results.
- [0078] The present disclosure may be embodied in many different forms, including, but in

no way limited to, computer program logic for use with a processor (e.g., a micro-processor, microcontroller, digital signal processor, or general purpose computer), programmable logic for use with a programmable logic device (e.g., a Field Programmable Gate Array (FPGA) or other PLD), discrete components, integrated circuitry (e.g., an Application Specific Integrated Circuit (ASIC)), or any other means including any combination thereof Computer program logic implementing some or all of the described functionality is typically implemented as a set of computer program instructions that is converted into a computer executable form, stored as such in a computer readable medium, and executed by a microprocessor under the control of an operating system. Hardware-based logic implementing some or all of the described functionality may be implemented using one or more appropriately configured FPGAs.

[0079] Computer program logic implementing all or part of the functionality previously described herein may be embodied in various forms, including, but in no way limited to, a source code form, a computer executable form, and various intermediate forms (e.g., forms generated by an assembler, compiler, linker, or locator).

[0080] Source code may include a series of computer program instructions implemented in any of various programming languages (e.g., an object code, an assembly language, or a high-level language such as Fortran, C, C++, JAVA, or HTML) for use with various operating systems or operating environments. The source code may define and use various data structures and communication messages. The source code may be in a computer executable form (e.g., via an interpreter), or the source code may be converted (e.g., via a translator, assembler, or compiler) into a computer executable form.

[0081] Computer-executable program code for carrying out operations of embodiments of the present disclosure may be written in an object oriented, scripted or unscripted programming language such as Java, Perl, Smalltalk, C++, or the like. However, the computer program code for carrying out operations of embodiments may also be written in conventional procedural programming languages, such as the "C" programming language or similar programming languages.

[0082] Computer program logic implementing all or part of the functionality previously described herein may be executed at different times on a single processor (e.g., concurrently) or may be executed at the same or different times on multiple processors and may run under a single operating system process/thread or under different operating system processes/threads.

[0083] Thus, the term "computer process" may refer generally to the execution of a set of computer program instructions regardless of whether different computer processes are executed on the same or different processors and regardless of whether different computer processes run under the same operating system process/thread or different

operating system processes/threads.

- [0084] The computer program may be fixed in any form (e.g., source code form, computer executable form, or an intermediate form) either permanently or transitorily in a tangible storage medium, such as a semiconductor memory device (e.g., a RAM, ROM, PROM, EEPROM, or Flash-Programmable RAM), a magnetic memory device (e.g., a diskette or fixed disk), an optical memory device (e.g., a CD-ROM), a PC card (e.g., PCMCIA card), or other memory device.
- [0085] The computer program may be fixed in any form in a signal that is transmittable to a computer using any of various communication technologies, including, but in no way limited to, analog technologies, digital technologies, optical technologies, wireless technologies (e.g., Bluetooth), networking technologies, and internetworking technologies.
- [0086] The computer program may be distributed in any form as a removable storage medium with accompanying printed or electronic documentation (e.g., shrink wrapped software), preloaded with a computer system (e.g., on system ROM or fixed disk), or distributed from a server or electronic bulletin board over the communication system (e.g., the Internet or World Wide Web).
- [0087] Hardware logic (including programmable logic for use with a programmable logic device) implementing all or part of the functionality previously described herein may be designed using traditional manual methods, or may be designed, captured, simulated, or documented electronically using various tools, such as Computer Aided Design (CAD), a hardware description language (e.g., VHDL or AHDL), or a PLD programming language (e.g., PALASM, ABEL, or CUPL).
- [0088] Any suitable computer readable medium may be utilized. The computer readable medium may be, for example but not limited to, an electronic, magnetic, optical, electromagnetic, infrared, or semiconductor system, apparatus, device, or medium.
- [0089] More specific examples of the computer readable medium include, but are not limited to, an electrical connection having one or more wires or other tangible storage medium such as a portable computer diskette, a hard disk, a random access memory (RAM), a read-only memory (ROM), an erasable programmable read-only memory (EPROM or Flash memory), a compact disc read-only memory (CD-ROM), or other optical or magnetic storage device.
- [0090] Programmable logic may be fixed either permanently or transitorily in a tangible storage medium, such as a semiconductor memory device (e.g., a RAM, ROM, PROM, EEPROM, or Flash-Programmable RAM), a magnetic memory device (e.g., a diskette or fixed disk), an optical memory device (e.g., a CD-ROM), or other memory device.
- [0091] The programmable logic may be fixed in a signal that is transmittable to a computer using any of various communication technologies, including, but in no way limited to,

analog technologies, digital technologies, optical technologies, wireless technologies (e.g., Bluetooth), networking technologies, and internetworking technologies.

[0092] The programmable logic may be distributed as a removable storage medium with accompanying printed or electronic documentation (e.g., shrink wrapped software), preloaded with a computer system (e.g., on system ROM or fixed disk), or distributed from a server or electronic bulletin board over the communication system (e.g., the Internet or World Wide Web). Of course, some aspects may be implemented as a combination of both software (e.g., a computer program product) and hardware. Still other embodiments of the may be implemented as entirely hardware, or entirely software.

[0093] While certain exemplary aspects have been described and shown in the accompanying drawings, it is to be understood that such aspects are illustrative, and that the embodiments are not limited to the specific constructions and arrangements shown and described, since various other changes, combinations, omissions, modifications and substitutions, in addition to those set forth in the above paragraphs, are possible.

[0094] Those skilled in the art will appreciate that various adaptations, modifications, and/or combination of the just described embodiments can be configured. Therefore, it is to be understood that, within the scope of the appended claims, the disclosure may be practiced other than as specifically described herein. For example, unless expressly stated otherwise, the steps of processes described herein may be performed in orders different from those described herein and one or more steps may be combined, split, or performed simultaneously.

[0095] Those skilled in the art will also appreciate, in view of this disclosure, that different embodiments or aspects described herein may be combined to form other embodiments.

Reference Signs List

[0096] 1 Combustion chamber, cylinder
2 Piston
3 Intake valve
4 Exhaust valve
5 Injector
6 Spark plug
7 Spray jet

Claims

- [Claim 1] Method for controlling a fuel injection of an internal combustion engine, the internal combustion engine comprising at least one cylinder, in which a combustion chamber is formed by a cylinder wall, a cylinder head and a top of a piston, the piston moving reciprocally in the cylinder driven by a crankshaft, at least one fuel injector configured to inject fuel into the combustion chamber, and at least one control device configured to control the fuel injection, wherein the fuel injection is controlled by comparing a calculated spray penetration length of fuel to be injected into the combustion chamber with a spray penetration length threshold at predetermined time points of an injection cycle, the first predetermined time point being an end of the injection cycle, generating a fuel injection profile comprising multiple fuel injections by setting an injection signal to a positive value at the predetermined time points of the injection cycle in which the calculated spray penetration length is smaller than or equal to the spray penetration length threshold, and resetting the injection signal to zero at the predetermined time points of the injection cycle in which the calculated spray penetration length exceeds the spray penetration length threshold until a fuel amount calculated on the basis of the previously generated fuel injection profile exceeds a predetermined fuel amount, and sending the generated fuel injection profile to the injector for performing the injection.
- [Claim 2] The method according to claim 1, wherein the spray penetration length threshold is determined depending on a position of the piston and a predetermined combustion mode.
- [Claim 3] The method according to claim 1, wherein the spray penetration length of fuel to be injected is calculated using a physical model, which considers the fuel pressure, the fuel temperature and the conditions in the combustion chamber.
- [Claim 4] The method according to claim 1, wherein a start of an injection is determined by a backward calculation at a time when the calculated spray penetration length exceeds the spray penetration length threshold.
- [Claim 5] The method according to claim 1, wherein a time period of the fuel injection profile between a falling edge by resetting the injection signal

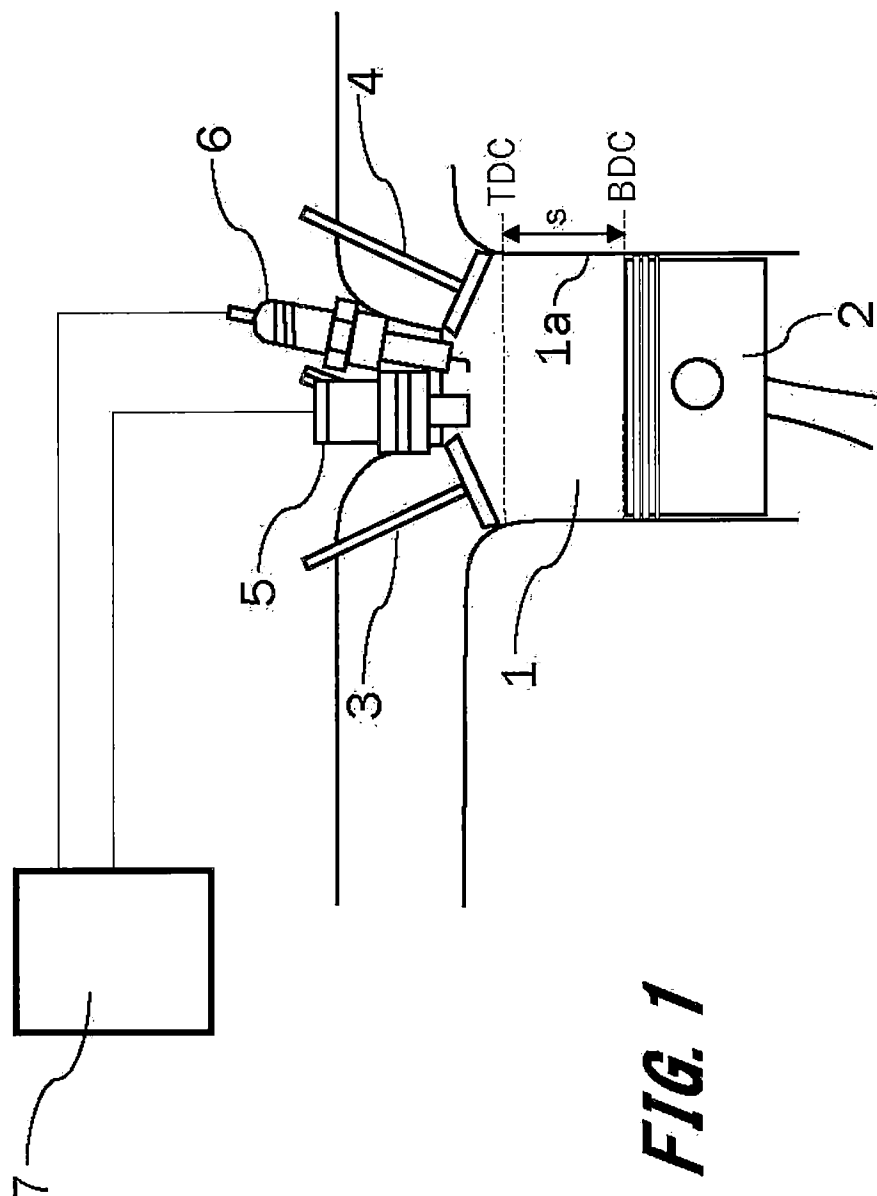
- to zero and a subsequent rising edge by setting the injection signal to the positive value is longer than a predetermined time threshold.
- [Claim 6] The method according to claim 1, wherein the end of the injection cycle is determined depending on the predetermined combustion mode in relation to an ignition timing of the internal combustion engine.
- [Claim 7] The method according to claim 1, wherein the fuel injection profile is generated by a backward calculation beginning at the end of the injection cycle, wherein a rising edge determined as the first characterizes an end of a last injection, and a falling edge determined as the last characterizes a start of a first injection.
- [Claim 8] The method according to claim 1, wherein the fuel amount calculated on the basis of the previously generated fuel injection profile is determined each time the injection signal is reset by calculating a fuel amount of an injection corresponding to a time period between a last falling edge and a previous rising edge of the fuel injection profile using a physical hydraulic model, and adding the calculated fuel amount to a sum of previously calculated fuel amounts until the sum of previously calculated fuel amounts exceeds the predetermined fuel amount.
- [Claim 9] The method according to claim 7, wherein the start of the first injection is determined based on a difference between the fuel amount calculated on the basis of the previously generated fuel injection profile and the predetermined fuel amount.
- [Claim 10] The method according to claim 1, wherein the predetermined time points of the injection cycle at which the fuel injection profile is determined are arranged at equidistant intervals with respect to a crankshaft angle of the internal combustion engine.
- [Claim 11] Control device for an internal combustion engine, the internal combustion engine comprising at least one cylinder, in which a combustion chamber is formed by a cylinder wall and a top of a piston, the piston moving reciprocally in the cylinder driven by a crankshaft, at least one fuel injector configured to inject fuel into the combustion chamber, wherein the control device is configured to perform the method according to claim 1.
- [Claim 12] Internal combustion engine comprising at least one cylinder, in which a combustion chamber is formed by a

cylinder wall and a top of a piston, the piston moving reciprocally in the cylinder driven by a crankshaft,
at least one fuel injector configured to inject fuel into the combustion chamber, and the control device of claim 11.

[Claim 13]

A computer program product storable in a memory comprising instructions which, when carried out by a computer, cause the computer to perform the method according to claim 1.

[Fig. 1]



[Fig. 2]

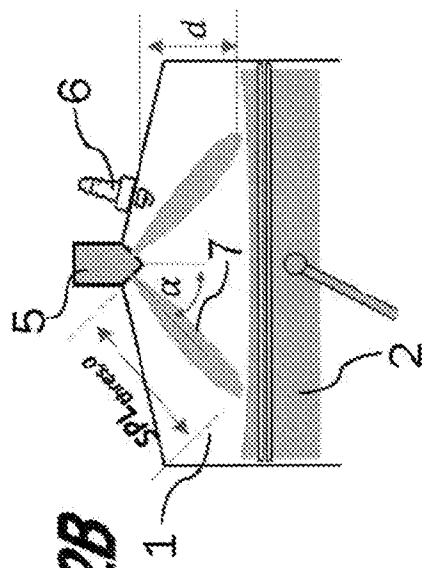


FIG. 2B

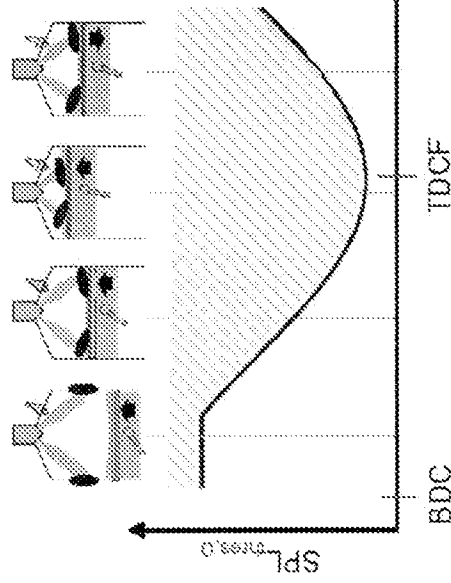


FIG. 2A

FIG. 2D

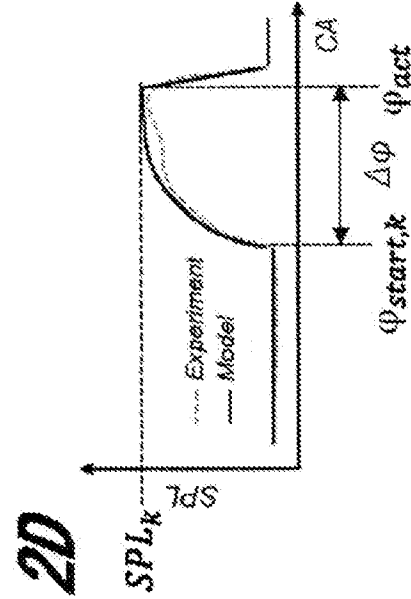


FIG. 2F

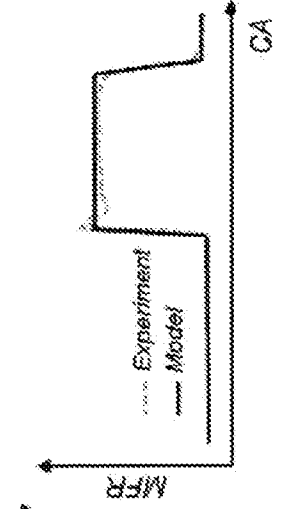


FIG. 2C

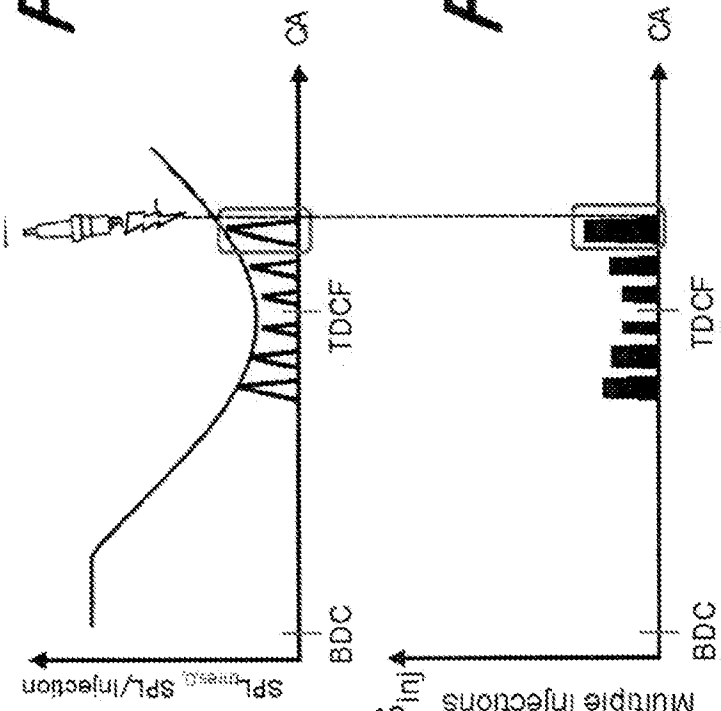
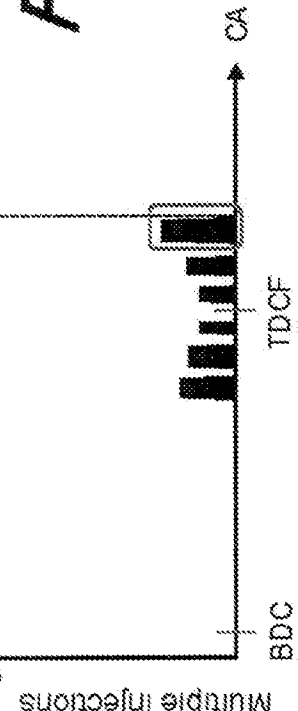
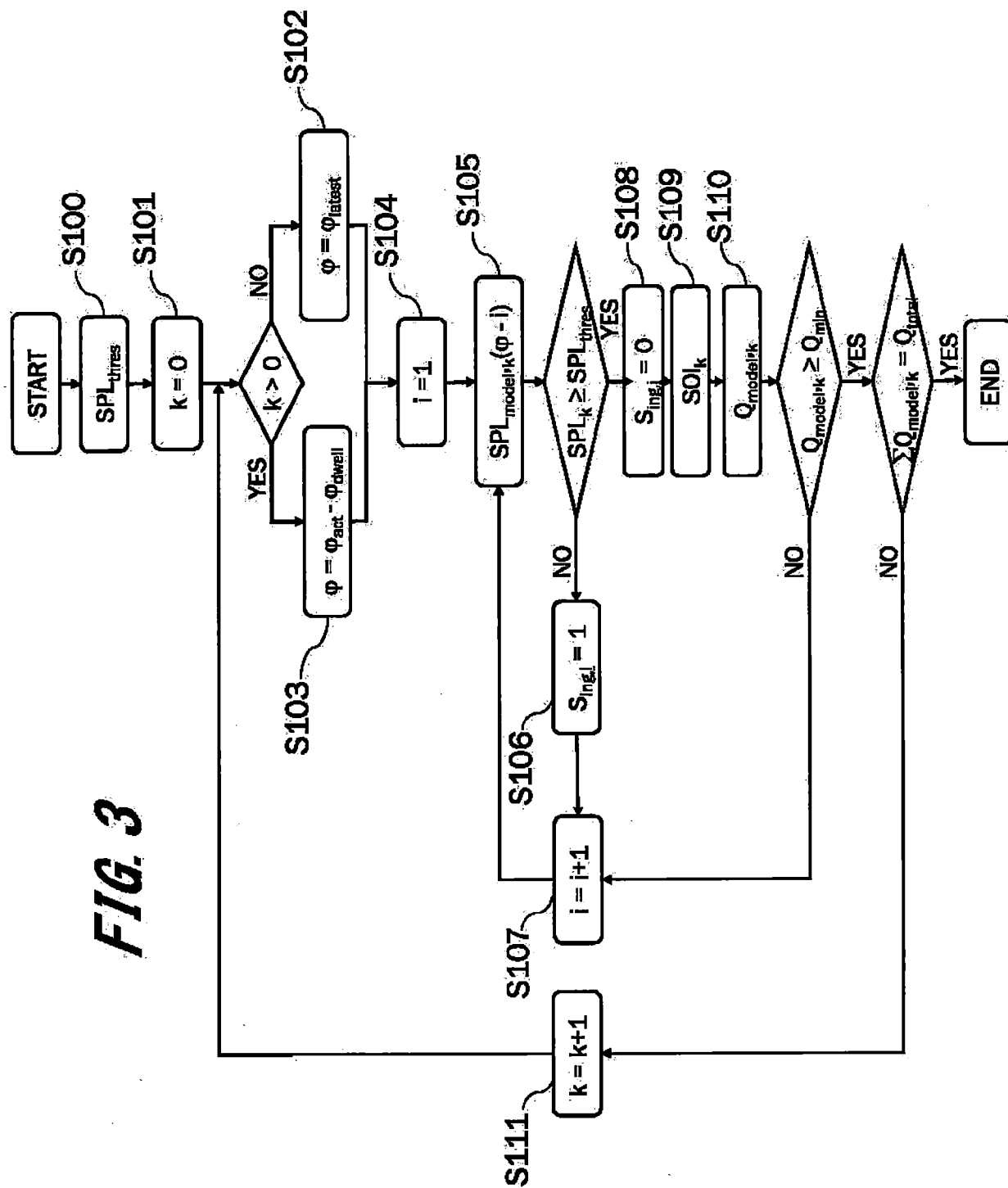


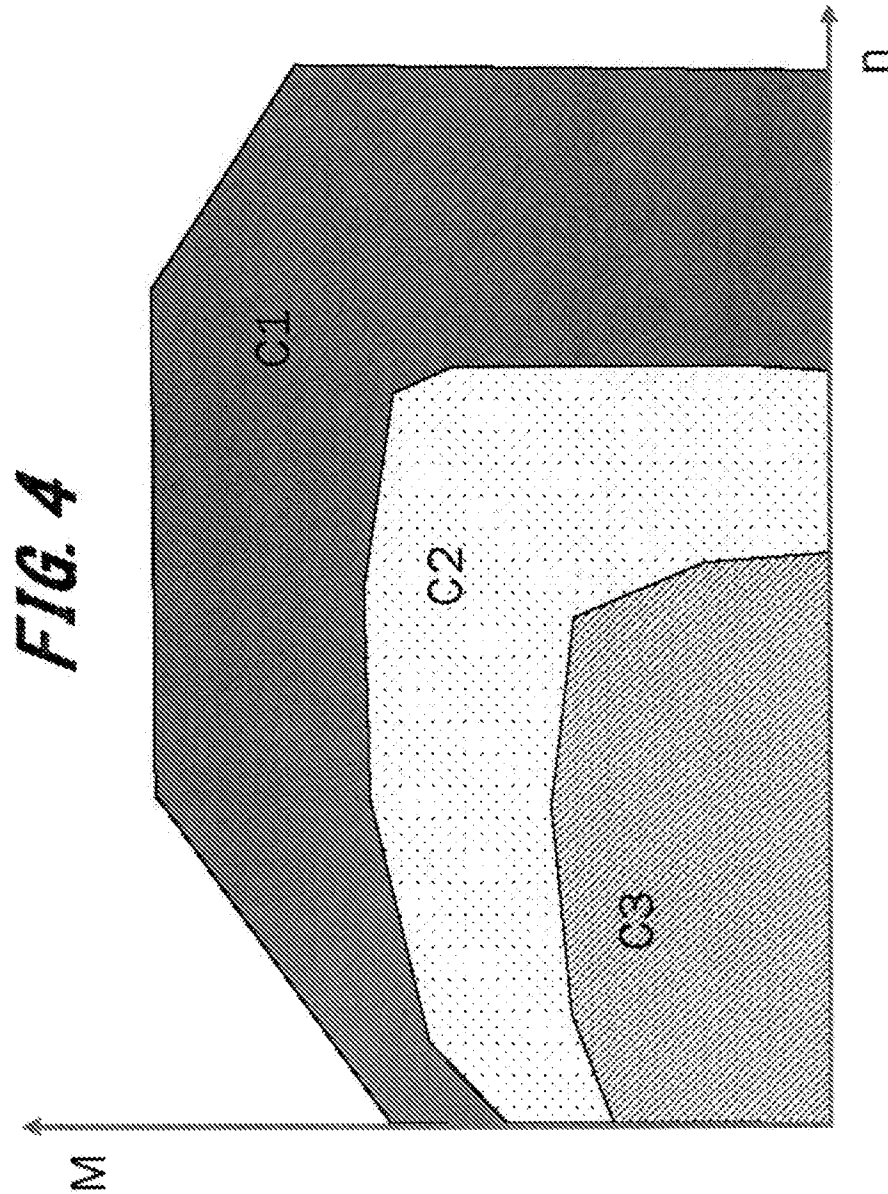
FIG. 2E



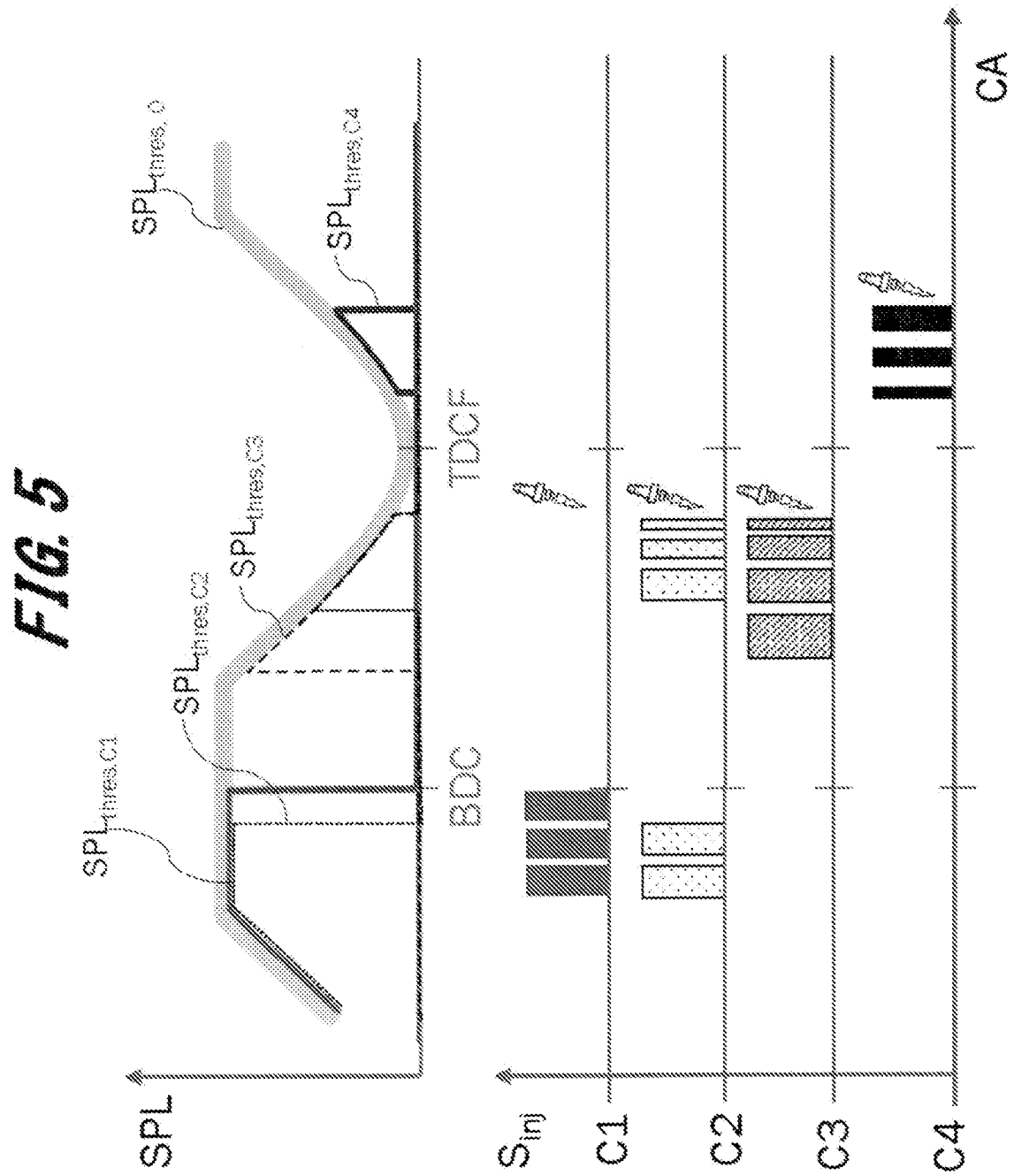
[Fig. 3]



[Fig. 4]



[Fig. 5]



[Fig. 6]

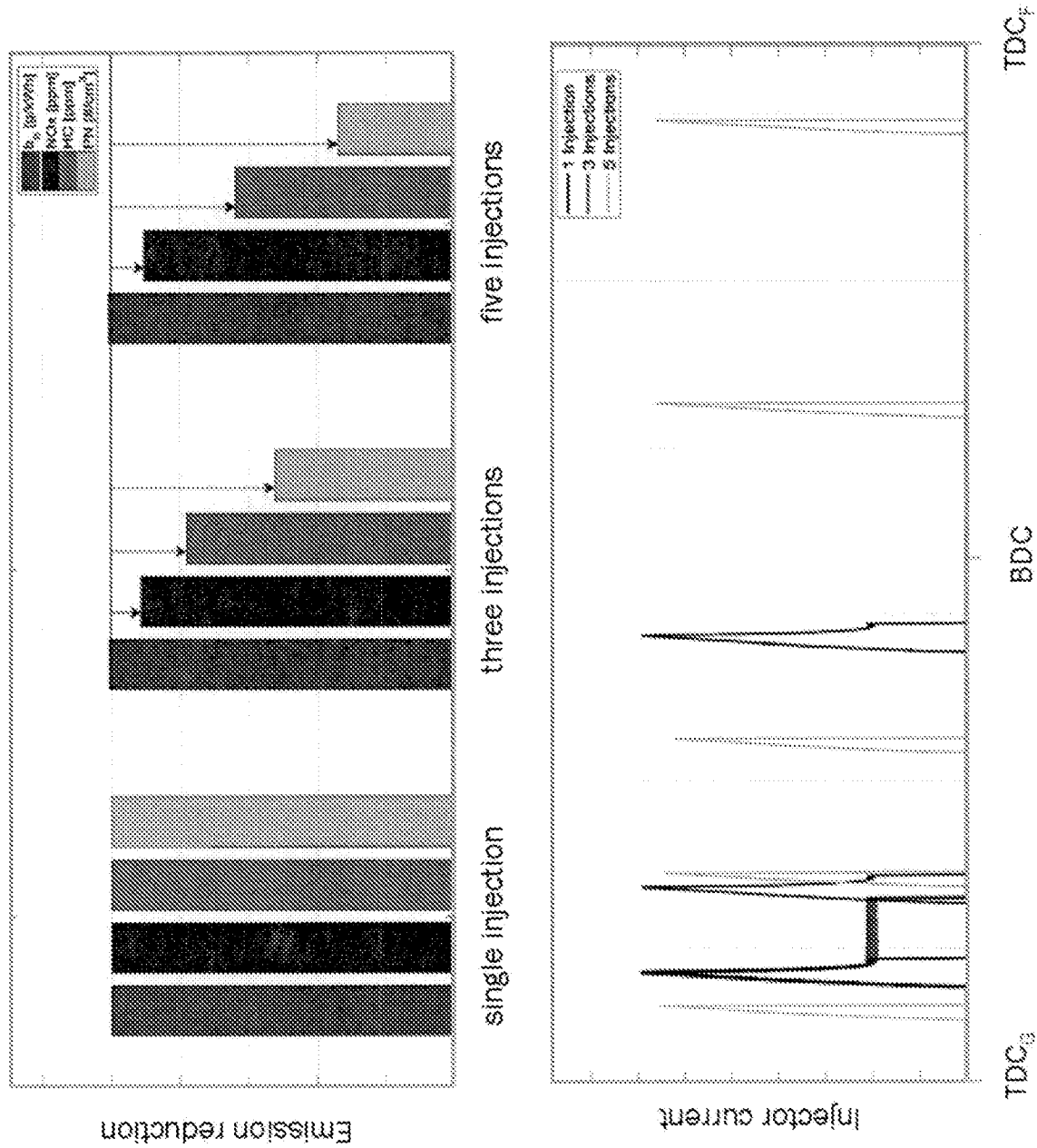


FIG. 6A

FIG. 6B

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2022/037304

A. CLASSIFICATION OF SUBJECT MATTER**F02D 41/40**(2006.01)i; **F02M 51/00**(2006.01)i

FI: F02D41/40; F02M51/00 A

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F02D41/30-41/40; F02M51/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Published examined utility model applications of Japan 1922-1996
 Published unexamined utility model applications of Japan 1971-2022
 Registered utility model specifications of Japan 1996-2022
 Published registered utility model applications of Japan 1994-2022

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2011/0155097 A1 (HITACHI AUTOMOTIVE SYSTEMS, LTD.) 30 June 2011 (2011-06-30)	1-6,8,10-13
A	paragraphs [0050]-[0061],[0092]-[0128], figures 4-6,18-24	7,9
A	JP 2009-133278 A (TOYOTA MOTOR CORPORATION) 18 June 2009 (2009-06-18) paragraphs [0032]-[0037], figures 4-5	1-13

☐ Further documents are listed in the continuation of Box C.☒ See patent family annex.

* Special categories of cited documents:

“A” document defining the general state of the art which is not considered to be of particular relevance
 “E” earlier application or patent but published on or after the international filing date
 “L” document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
 “O” document referring to an oral disclosure, use, exhibition or other means
 “P” document published prior to the international filing date but later than the priority date claimed

“T” later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
 “X” document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
 “Y” document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
 “&” document member of the same patent family

Date of the actual completion of the international search

13 December 2022

Date of mailing of the international search report

27 December 2022

Name and mailing address of the ISA/JP

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INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.

PCT/JP2022/037304

Patent document cited in search report			Publication date (day/month/year)	Patent family member(s)			Publication date (day/month/year)
US	2011/0155097	A1	30 June 2011	CN	102108909	A	
				EP	2339158	A2	
				JP	2011-132898	A	
JP	2009-133278	A	18 June 2009	(Family: none)			