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Week - 07
Lecture – 26

Lec 26: An overview of injection duration calculation

I welcome you all to the session on engine system and performance. Today, we shall discuss the methods of calculating injection duration time. So, if we try to recall, in our last class, we discussed the electronic fuel injection system, and from our previous discussion, we had seen that the injection duration is very important, essentially from the perspective of fuel economy and engine efficiency. Most importantly, if we can design the proper pulse width and also the frequency of pulses, certainly engine efficiency will increase, and above all, emission levels can be controlled. So today, we shall discuss a few aspects—rather, methods of calculation for injection pulse width, or to be precise, injection duration calculation.

So, injection duration calculation is basically a two-step process. The two different steps are basic injection duration calculation and the second one is injection calculation correction factors. So, if we write that injection duration calculation, this is basically a two-step process. And if it is a two-step process, then what are these two steps? The first one is basic injection duration—that is, basic injection duration calculation or calculation of basic injection duration. The second is injection duration correction factors. So, you can understand we need to have proper, or rather, optimum injection duration. Essentially, fuel injection—electronic fuel injection system—is a part of the electronic control system, and the ECU will give some signal to the driver unit to operate injectors to have the proper duration. As I said, proper calculation of injection duration—that is, the time duration of fuel injection—is very important to improve fuel economy as well as to reduce emissions. So, this involves two different processes. The first is basic injection duration calculation—that means we first have to calculate the basic injection duration, then after determining the basic injection duration, we can apply some corrections to this step, essentially to match the required injection duration—or the required duration to run the engine, not always at optimum condition, but closer to the optimum condition.

So, these are two different steps. Now, if we now elaborate on the first step, so if we go to the next slide, that is basic injection duration calculations. So, this particular step, basic injection duration is reliant on a few input sensors. So, there are ECU or electronic control unit is reliant on a few input signals. Those will be received from different sensors.

The basic injection duration is reliant on a few input sensors and these input sensors are number one is certainly engine speed, second one is air flow meter and then very important is, that manifold absolute pressure. This is also very important. So, these three sensors are very important for the calculation of basic injection duration. Electronic control unit, determines basic injection duration based on engine RPM and air flow volume. So, that means the amount of air is drawn into the engine cylinder during intake stroke together with what is the speed of the engine, these two particular quantities, are very important. So, basic injection duration calculation is based on the engine speed and air flow volume. So, air flow meter sensor will give some input to the ECU about the mass of air is drawn into the engine cylinder. Similarly, engine speed sensor will give some input to the ECU.

The speed at which engine is running. Based on these two input parameters or based on these two quantities will be received by the ECU from these two sensors, basic injection duration is calculated. To be precise, these two parameters or these two quantities rather not parameters, engine speed and air flow volume, these two quantities are regarded as the engine load factor. And so, engine speed and air flow volume are the engine load factors. These two quantities are regarded.

Now question is if any of these two parameters or say as either of these parameters increase, basic injection duration is increased. Quite obvious, that if engine speed increases, certainly fuel that needs to be supplied to the cylinder should increase. Similarly, to meet the load of the engine, if we need to develop or if the engine needs to develop more power, if we need to extract more power from the engine, air volume, air flow volume should be more. If air flow volume or more amount of air is drawn into the engine cylinder to burn that assuming that the ratio is always trisometric, more amount of fuel should be supplied.

So, these two parameters are very important and as either of these parameters increase, injection duration is increased. It is important to mention here that electronic control unit cannot operate if any one of these two quantities is faulty. That means electronic control unit has to receive proper input from engine speed sensor and intake air flow meter sensor. So, that is the air mass of air or volume of air drawn into the engine cylinder.

So, now how it is possible for an injector or for the ECU to give some input to the driver circuit of injector to provide or to open. Essentially, you have studied in internal combustion engine course that fuel injectors, there is a needle and that needle has to lift or that will be pulled by the injector to open the gap. and through that gap, fuel should be injected into the engine cylinder. Now the question is, how much that needle would be raised or that lift of the needle from the sitting place.

Needle is always spring loaded, so it will always, the normal tendency of the needle is to remain seated over there, but if we have some mechanism to lift the needle from its initial position, we can have some opening area. Through that opening area, certain amount of fuel or metered quantity of fuel should be injected. So that injector control unit should be capable of giving some, forcing to lift the needle and that would be again controlled by the electronic control unit. So, let us now discuss about the procedure of functioning a particular injector to calculate basic injection duration.

So, what is done a basic injection output signal is derived from a stored characteristic map. See this map is stored on the chip of ECU. So basically, this characteristics map forms a part of read-only memory that you have studied, read-only memory chip in the ECU.

So, this characteristic map forms a part of the read-only memory chip in the ECU. So, this map is already stored. So, we have to have this map. Now, in this map, essentially, this map is prepared. So, this is the characteristic map.

So, there are throttle opening. So, this is the throttle opening angle (TOA), and this is engine speed (ES). Now, this map is prepared based on some data. So, basically, this TOA stands for throttle opening angle, and ES stands for engine speed.

So, typically, what is done is, 15 throttle opening angles are considered to develop this map and 15 engine speeds. So, we consider 15 data points for throttle opening angle and 15 data points for engine speed. So, what is throttle opening? So, different throttle opening angles indicate.

Full throttle opening, throttle is fully closed, throttle is fully open. That means this is very important: how far the throttle is open. So, this is essentially the indication of throttle opening angle—how far the throttle valve is open. Similarly, we can have 15 engine speeds. So, you can see we can have 15 by 15, that is 225 data points. To prepare this table—is prepared based on these 225 data points.

And these 225 data points, for a given throttle opening angle, for a given speed, this table is prepared. And this table is prepared based on the output from extensive engine trials. And these extensive engine trials are conducted at a stoichiometric air-fuel ratio. So, using a stoichiometric air-fuel ratio or considering a stoichiometric air-fuel ratio, if we perform engine tests and, based on the engine tests, if we can figure out—if the throttle opening angle is 15 degrees, then what should be the speed?

Following this, we can have these 225 data points and having this table. This table is stored in the ECU. And this table forms a part of read-only memory in the ECU. Now the question is to speed the—so this is an essential lookup table. So, this is a lookup table.

So, to increase the speed of the lookup table, no interpolation is allowed. That means had we conducted test considering stoichiometric air flow ratio then if we could measure engine speed, say for example at 15-degree throttle opening and then also 20-degree throttle opening, no interpolation is allowed in this lookup table to know the engine speed in between these two throttles opening angles that is 15 degree and 20 degree.

So, this is essentially done to increase the speed of the lookup table. So now the question is, if that is the case, then there can be a deviation in this lookup table. Then what remedial action is or step is taken? So that means if there is a deviation from this lookup table, then what remedial measure is taken by the ECU to operate injectors?

if it is a multi-cylinder engine, of course. So, now question is to do that, an adaptive map with 8 into 8 data points is built onto the basic characteristic map. Now, if there is any deviation, no interpolation is allowed essentially to increase the speed of the lookup table, but if there is any deviation. So, if a given deviation on the basic characteristic map is exceeded, an adaptive algorithm installs correctional values onto the adaptive map. So, this is very important. First of all, what we have discussed that this characteristic map is prepared based on 225 data points. and these 225 data points are obtained from extensive engine trials considering stoichiometric air-fuel ratio. And to increase the speed of the lookup table, no interpolation is allowed.

So, if there is a deviation, then what remedial measures should be taken by the ECU to operate injector? So, to do that, what is done? If a given deviation on the basic map is exceeded, an adaptive algorithm installs correctional values onto the adaptive map. So, now this adaptive algorithm which is based on some evolution of signals received from a special sensor and that is known as lambda sensor. So, a special sensor should be integrated to that circuit and that sensor is responsible to provide some signal or input based on that input this adaptive algorithm will do some corrections and those correctional values are mapped onto this adaptive table and that adaptive table is built onto this basic table. So, this way some remedial or some preventive measure is taken to increase the sensitivity or efficacy of the control unit, so as to allow injector to operate even there is any deviation. So, this is the first step. And this particular basic map forms a part of read-only memory in the ECU.

The second point is that we have discussed. Our second step is injection duration corrections factors. So, try to understand having establish the basic injection duration by the control unit, then we need to go for some correction over the first step that is basic injection duration.

Now, why do we need to have this particular step. Because in the beginning we had mentioned that basic injection duration calculation is reliant on a few sensors or input sensors and those input sensors are engine speed sensor, air flow meter sensor and manifold air pressure, absolute pressure sensor. Now question is there are many other sensors which are responsible to give some input to the ECU and those sensors are engine coolant temperature sensor, intake air temperature sensor, exhaust gas, so the sensor which is responsible to sense the presence of oxygen in the exhaust gas. So, all the sensors can give some input to the ECU and then ECU on receiving signals from the sensors corrects.

The basic injection duration time, so as to comply with the exact requirement for the engine. So, basically that basic injection duration is calculated or determined. Now, this basic injection duration calculation should be corrected so as to meet the actual requirement and that is why the second step is necessary. So, this particular step, basic injection duration is calculated using the lookup table that we have discussed a few minutes back.

So, basic injection duration is calculated by using the lookup table which is already built in. Now, the second step—so that is already there—the second step is the correction or introduction of a correction factor, calculation of a correction factor, or correction over the first step. So, the second step involves the correction over the first step.

To do these corrections, essentially, the basic injection duration is calculated—that is fine—using the lookup table. Now, the basic injection duration may not be the actual duration needed for the engine. So, to run the engine—if we need to run the engine always at the best efficiency— and if we need to ensure that the emission level should be under control or the emission level should be reduced, we always need to have some correction over the basic injection duration.

And those corrections are again reliant on the signals from a few input sensors. And those input sensors are used for the correction of the basic injection duration. And if we now mark this particular line, we need to rely on a few input sensors essentially to correct the basic injection duration, and those input sensors are: number one, the engine water temperature sensor. To be precise, I should write in a more generalized form: that is, the engine coolant temperature sensor.

b) is, that is, throttle position. c) is intake air temperature sensor, and d) is exhaust gas oxygen sensor. So, all these sensors are again very much responsible for giving some input to the control unit, essentially to correct the basic injection duration so as to allow the injector to operate properly. Now, let us discuss one by one how all these sensors can correct the basic injection duration. Let us now consider some of these correction factors in some detail.

So, if we go to the next slide, if the engine coolant temperature or the intake air temperature increases or moves from cold to warm, then certainly you can understand. If intake air temperature increases or engine water temperature increases, that is obvious that, the fuel injection duration should be reduced. Because we have no need to supply an additional amount of fuel to accommodate the effect that may arise due to a reduction in engine water temperature or engine coolant temperature, as well as the temperature of incoming air. Similarly, if the engine needs to open the throttle, or if the engine needs to have a wide-open throttle because of a sudden requirement of engine load, then immediately or momentarily, the frequency of the injection pulse should be increased momentarily. Otherwise, it is very difficult. So, if a particular engine needs to produce more load, more power, the throttle should be wide open, which means more air should be drawn into the engine cylinder. To burn that additional amount of air, we need to supply an additional amount of fuel. That is what you have learned. Now, if we need to supply more fuel, the injection duration should be even longer, and that is essentially sensed by the throttle opening sensor. Next is the exhaust gas oxygen sensor.

So, the exhaust gas oxygen sensor—what does it mean? If the sensor, which is placed on the exhaust manifold, essentially senses the presence of oxygen in the exhaust gas or exhaust gases—if a certain amount of oxygen is there in the exhaust gases, it means that the air that was drawn into the engine cylinder is still remaining unburnt. So, the total amount of air was not—or has not been—used by the fuel that was introduced into the engine cylinder for its burning. Thus, it is incomplete combustion; burning is not proper. So that means, again, some corrections are needed to accommodate that particular aspect. So, all these sensors are responsible for correcting the basic injection duration—that you can understand.

If the exhaust gas oxygen sensor—that is, the sensor used to sense the presence of oxygen in the exhaust gases—detects oxygen and if that particular level exceeds the threshold value, then immediately the injection has to swing—or the injection period swings—back and forth between longer and shorter durations, essentially to adjust to the required or allowed oxygen level in the exhaust gases. So now, I will discuss one-by-one corrections for intake air temperature. The first one is correction for intake air temperature.

Why do we need to correct this? Why do we need to use this particular sensor—or consider this particular temperature, the intake air temperature—to correct the injection duration? So, that depending on the temperature of the ambient air, the density of the air will change, which in turn will change the mass or volume of air drawn into the engine cylinder.

So, we all know that if the air is cold, it will be denser. So, that means, depending on the ambient temperature, some corrections are needed for the injectors to supply the required quantity of fuel so as to have or so as to maintain close to the stoichiometric air-fuel ratio for the burning of the fuel—or for efficient combustion. So, the colder the air, the denser it becomes, as we all know. Now, if for this reason, the density of air changes with temperature, and if it changes, then this correction factor—and for this reason, a correction factor or correction coefficient is used for, considering changes in air temperature.

Essentially, you can understand that if air temperature changes, the volume of air or mass of air drawn into the engine cylinder will change. But if we need to have proper combustion, an adequate amount of fuel should be supplied. If we need to supply an adequate amount of fuel for that particular mass of air drawn into the engine cylinder during the intake stroke, this injection duration time should be corrected. So that is what it is.

So, if we try to discuss this part with some graphical or coefficient graph. If we use a correction coefficient—β correction factor or correction coefficient β. I will be using a suffix. Something to indicate.

Whether that correction coefficient, is for air temperature. or correction coefficient for coolant temperature, correction coefficient for Exhaust gas oxygen all these things. So, we are discussing now. Correction coefficient for intake air temperature.

So, β_{IAT}. This is the variation and this is inlet air temperature that is IAT. So, the reference temperature, the correction factor is unity or 1 when this is 25℃.

So, this is 1. Now, if the intake air temperature is less than 25℃. So, if it the colder, the air temperature that denser it becomes. So, if the correction temperature is less than 25℃ here, then you can see say for example, this becomes 1.1 or it may so happen that the inlet air temperature is greater than 25℃, then it may be like this. So, this is 0.9. So, depending on the inlet air temperature, we can see that β_{IAT} that is correction coefficient for inlet air temperature changes from the reference point. So, this is the reference point.

What does it mean? That means injection duration has to reduce by 10 percent if temperature increases beyond 25℃. Injection duration should be increased by 10 percent that is 1.1, if the intake air temperature falls below 25℃. So, that is what it is and that correction or adjustment should be taken care by the control unit to allow injector, to supply required or adequate amount of fuel as needed by the engine.

If we go to the next one that is correction for coolant temperature. So, that is engine water temperature, engine coolant temperature. Again, if I draw the coefficient graph. So, this is coolant temperature. So, this is coolant temperature (CT).

and this is β_{CT}. So, correction coefficient or correction factor for coolant temperature and the reference value is, if we draw the reference value is 1 when this is 70℃. So, this is 1. Now, the coolant temperature will certainly be higher So, engine water temperature and engine coolant temperature.

So, if engine coolant temperature increases beyond 70℃, certainly the coefficient this. So, this is coolant temperature. 70℃ is a coolant temperature that is engine water temperature. So, it is not possible or it is not allowed to have boiling of water in the cooling water jacket.

So, essentially if the coolant temperature is less than 70℃. So, below the reference temperature if we draw here, then injection duration is increased. So, if it is, say 1.2. So, if the coolant temperature is below the reference temperature.

So, this point is the reference point. So, when engine is cold certainly coolant temperature will be less. So, when engine is cold then fuel vaporization is relatively poor until intake manifold, until warms up and this particular problem is known as this particular problem. That if the engine is cold then fuel evaporation evaporation is relatively poor until intake manifold is warmed manifold warms up and this particular problem is known as lean drivability. So, lean drivability problem is associated with this, that means if engine is cold. So, if the engine coolant temperature is less than 70℃, that means engine is cold. And in such a case, in such a condition, we need this correction that if it is a case, then maybe we have to increase 20 percent injection duration depending upon the requirement. At extremely cold condition, it may require that the we need double that is 100 percent even increase in the fuel injection period. So, that is based on the engine requirement.

So, what we can understand that depending on the engine temperature which can be better understood by the coolant engine temperature sensor. If engine is cold, fuel evaporation would be affected and it will lead to a problem that is known as lean drivability. And to circumvent or to alleviate this particular problem, what we need to do, we need to take into account this particular correction so as to increase the fuel injection period or duration.

And then next one is power enrichment correction. So, this is again, for this correction, engine needs to rely on, or not only engine, the electronic control unit needs to rely on MAP, that is manifold absolute pressure sensor. Let me go back to previous two slides. Correction for coolant temperature, so this is, for this correction, ECU is dependent on or reliant on engine coolant temperature sensor. If we go to the next slide or previous slide again, so correction for intake air temperature, if we write here, so again ECU should rely on some sensor for this correction and that sensor is intake manifold.

air temperature sensor. So, we can understand that we have discussed that second step is reliant on a few input sensors. The first one is reliant on intake manifold air temperature sensor. Second one is on engine coolant temperature sensor. Third one that we are going to discuss is reliant on manifold air pressure sensor.

So again, if we try to draw the curve, that is the correction coefficient for power enrichment correction. So, this is, intake air volume or throttle angle.

So, here it is called β_{PE}. So, this PE stands for power enrichment. So, this is something like this.

If we draw the curve. So, this is 1. And what we can see. So, this is the reference one, correction factor one, which means no further correction is needed. So, it is fine.

If the intake air volume or throttle opening angle is becoming more so as to adjust with the power enrichment or so as to increase the power, certainly the coefficient should increase that you can see from the curve. So, in this range, no correction is needed. no correction is needed for this range of intake air volume and throttle angle. So, now let me tell you one thing, why do we need to have this? All of a sudden, if engine needs to deliver moderate to heavy loads, then if we demand more power from the engine, certainly injection duration should be higher. So, to increase the power or load that would be produced by the engine, we need to have or we need to open the throttle opening so as to allow more amount of air into the engine. Now, to have that much power, we need to supply adequate amount of fuel to maintain stoichiometric air-fuel ratio. So, if the volume of air is increased or volume of air drawn into the cylinder is becoming more, then certainly we need to or the injectors or the control units should give some feedback to the injector to supply more amount of fuel so as to maintain stoichiometric air-fuel ratio. And that is why this particular correction factor should be taken into account if the throttle opening angle is becoming or increases beyond this value.

So, if for this range, correction is needed that you can understand. So, this is essentially power enrichment. So, power enrichment is very important. So since electronic control unit should be flexible enough to meet the demand, certainly all these facilities should be built in so as to allow engine to meet the requirement, to meet the demand.

So now, if we go to the last one, that is known as battery voltage correction. So, the final one is the battery voltage correction. So, this is called battery voltage correction. So, why is this important?

Battery voltage correction. For any fuel injectors, this needle movement is again controlled by the magnetic plunger, and we need to know that the movement of the magnetic plunger is again controlled by some battery. So, we need to allow that magnetic plunger, which is essentially a core with copper wire wound around it. Over the core, and then we need to allow current to flow through the copper wire. The magnetic plunger is fabricated using any particular core of iron, an iron core, and the iron core is wound with copper wire. If we need to supply current through the copper wire, then we can have a magnetic field. And so, basically, that current is allowed to flow through the copper wire using a battery.

Now, if the battery voltage drops, the amount of current that will flow through the wire will also reduce. So then, the movement of the magnetic plunger should be affected. If the movement of the magnetic plunger is getting affected, certainly the movement of the needle should be affected. So, if the movement of the needle is affected, the fuel injection should be affected.

So, in a way battery voltage correction is needed so as to adjust the delay associated with all these issues. So, just I will write one or two points here that one is called operational delay. So, first of all if the voltage of the battery varies it is likely that the time taken to open the injectors will vary that is what I was telling that the injectors is controlled by the magnetic plunger and the movement of the magnetic plunger is again controlled by the current that will come from the battery.

So, this battery voltage drops then the amount of current that will flow through the magnetic coil will reduce which in turn will reduce the injector closing opening part. So, this is important. Now, the question is electronic control unit will give some signal to the driver circuit of the injector and receiving that signal driver circuit again will give some signal to the injector. So, there is a delay between these two times.

So, let me tell you one thing electronic control unit will give some signal to the battery driver circuit and that driver circuit again receiving some signal from ECU will give some signal to the injector. So, there is a time lag between these two and this is called operational delay. So, the time lag between time needed for ECU to give a signal to the driver circuit and time needed for the signal that will come from driver circuit to the injectors. So, there is a lag and this lag is called operational delay. Essentially, some correction should be taken by the battery voltage so as to take this particular correction.

So, important part is the delay. So, operational delay. What is this? So, delay between the time, the ECU sends the injection signal to the driver circuit and the actual opening and the actual opening of the injector. This is the operational delay. So, this delay changes with the strength of the magnetic field. So, now this delay will be again, changes with the strength of the magnetic field. around the injector coil.

So then delay is getting compounded, so this delay will increase if battery voltage drops. So, this delay increases as the battery voltage drops. So, to determine the fuel injection duration or final fuel injection duration ECU corrects this. ECU corrects for injector opening delay by using the battery voltage correction factor coefficient. So that is what you can understand. So, the operation delay should be again compounded because of the drop-in battery voltage because that is also related to magnetic field strength that magnetic plunger is responsible for the movement of the needle. Now, if the current passing through the magnetic coil is reduced, magnetic field will reduce which in turn will alter the needle movement. So, the operational delay is compounded and so, this delay changes with the strength of the magnetic field around the injector coil and hence to correct this, ECU needs some voltage correction factor and that is what it is. So, in case of a low amount fuel injection, a non-flammable mixture is prepared.

So therefore, minimum fuel injection limit or time limit, has to be defined to prevent formation of unborn hydrocarbons, in the exhaust gases. So, why? Why do we need to have some corrections over the first step?

Because if we do not make all these corrections, certainly if the fuel injection time is not proper, and if the amount of fuel injection is low, then what will happen? That a non-stoichiometric mixture is prepared. So basically, it is not stoichiometric. So, what will happen? The minimum fuel injection time limit has to be defined to prepare the formation of unburned hydrocarbons in the exhaust gas. So, essentially, this part—will increase the emission level.

So, the question is: if the engine's fuel requirement for a particular condition is low, the ECU should be able to supply, a metered quantity of fuel to prevent this undesirable phenomenon. So, that minimum time limit has to be defined by the ECU so that the injector can supply only a low amount of fuel if the situation demands it. And the last important point I would like to discuss is that whatever we have covered today essentially applies when the engine is under operation. But during engine start, the calculation of the fuel injection period is separate and is not dependent on whatever we have discussed in today's class.

To summarize today, we have discussed the injection time duration calculation steps. We have identified two different steps, discussed them in detail, and then we saw that a proper injection time duration is needed essentially to maximize engine efficiency and reduce emission levels.

With this, I will stop here today, and we shall continue our discussion in the next class.