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Sustainable use of Single-Cylinder Engine over Multi-Cylinder engine in Formula SAE/Formula Student Vehicle

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Abstract - *For formula style race cars, the selection of an engine decides whether a team wins the race or does not end in any respect. The set of rules of Formula SAE/Formula Student competitions allows the utilization of four-stroke engines of up to 710cc volumetric capacity with forced induction. Since many years, most teams around the world design their car around normally aspirated multi-cylinder 600cc engines. The suitability of an alternative single-cylinder engine is examined here through engine simulation. Moreover studying both single and multi-cylinder engines thoroughly will be beneficial to know benefits and drawbacks about each of them. Simulations are used to find the most appropriate configuration to be used in the FSAE/FS competitions. It is shown that in a normally aspirated setup, the single-cylinder engine is unlikely to be competitive, but if a light weight vehicle is manufactured, a very attractive overall vehicle package is found to be the result. However, additional intensive engine analysis has to be performed so as to upgrade the single-cylinder engine from naturally aspirated to forced induction model. As the program expands and develops, the team can set new goals for powertrain for future.*

Key Words: **FSAE, Formula SAE, FS, Formula Student, Automobile, Engine Selection, Single-Cylinder, KTM 390**

1. INTRODUCTION

Formula SAE/Formula Student, is a competition in which University students design, manufacture and compete in a formula style single seat racing cars [1] [2]. These competitions are held all over the world at more than 20 locations. Each year the organizers of the FSAE/FS competitions release a set of detailed rules, which all teams must follow closely to avoid disqualification. These rules are updated every year based on what the judges may have seen at previous year's competition. The rules are mandated to ensure all the participants' safety and also to ensure that no team has an unfair advantage. The judges want the winner to be determined solely based on the team's design. Most importantly, only four-stroke engines are allowed and the engine capacity cannot exceed 710cc [3]. Moreover, the air supplied to the engine should compulsorily go through a restrictor to limit the power. The diameter of this restrictor should be 20 mm if using conventional premium unleaded gasoline or 19mm if the engine runs on E85 bio-ethanol.
Keeping all these parameters in mind, there are several options for teams to determining the most effective engine for the design of their vehicle. Most of the teams similar to GT Motorsports (GTMS) [4], a formula student team which is run by students of Gujarat Technological University (GTU), Ahmedabad; use motorcycle engines of both single and multi-cylinder. Some teams are ambitious and design their own engines, while a few teams go with conventional car engines. The majority of teams opt for 600cc or 650cc sports motorcycle engine as their base [5]. These engines have high performance in their original configurations. For example, Yamaha R6, Honda CBR600, Suzuki GSX600 produces around 105-120 bhp in its production variants and are close to the maximum allowable engine capacity under the FSAE/FS rulebook.

However, such a power output isn't accomplishable in an FSAE configuration as a result of the airflow limiting, hence performance limiting, which are effects of the restrictor. These regulations open a new dimension for many teams to sacrifice the extra power and use a single cylinder engine. Moreover, there is a drop of around 30-35% in power due to the restrictor, which suggests that FSAE engines based on the 600cc motorcycle engines are under lower stress in this configuration than their original configurations [6]. This means that such engines are oversized and overweight for the FSAE application.

Determining which engine to use is principally based on the overall weight of the car. An average FSAE vehicle weighs around 150-160 kg without the engine and driver. The dry mass of these multi-cylinder engines falls within the range of 55-70kg. This represents a significant portion which is around 25% of the total car weight. The engine also claims a large space in the rear of the vehicle as seen in Figure 01.

Fig-1: FSAE Vehicle with 600cc engine in rear

A smaller, lighter engine would be preferable, if it could still be close to the performance of the 600cc FSAE configuration.

Such an engine would make up for a lighter car with a lower center of gravity and reduce the polar moment of inertia, yielding improvements in braking, handling, and acceleration. The ideal candidate for the above-mentioned requirements is Yamaha YZ450 or the KTM 450SX single-cylinder engines. They have a dry mass of only 27-30kgs and produce 45-60BHP. Seeing the Indian market and engine availability, best possible options are RE 500 EFI, KTM 390 and Honda CBR250R engines. They are a little heavier than the above two but give almost equivalent power outputs. The work detailed in this paper was therefore carried out to establish, if a competitive power output from such a single-cylinder engine can be achieved in an FSAE configuration.

2. ENGINE SELECTION CRITERIA

Constraints- The official FSAE rules lay down some restrictions on the engine. According to the rule IC1.1, the engine must be a piston engine using a four-stroke primary heat cycle with a maximum displacement of 710cc. All engines must also be fitted with a restrictor on the inlet to limit power. The diameter of this restrictor is 20 mm if using conventional premium unleaded gasoline or 19mm if the engine runs on E85 bio-ethanol [3].

Market Survey- The primary design decision in selection of an engine should be the number of cylinders and availability of engine. More cylinders offer increased and better-balanced power at the cost of greater weight and complexity. Moreover, it is equally difficult to procure a multi-cylinder engine and its parts when overhauling is required. An in depth market research was carried out to list down the available engines within the Indian market that meets the requirements for the competition. The following provides a brief description of the available options and concludes with a Weighted Design Matrix.

Single Cylinder- It is the simplest available engine and a common choice for most low budget FSAE teams. It consists of a single large cylinder through which all the combustion occurs and mechanical power is generated. This simplicity offers several direct and indirect benefits. They have fewer parts because there is only one moving cylinder which results in weight savings. A typical single cylinder engine will weigh only 30-35 kg enabling better fuel economy, handling, and acceleration. Fewer parts result in greater durability and reliability. However, these engines produce only ~50 Bhp and large vibrations reduce the comfort of the ride and may require additional damping. Benefits are the low cost of maintenance and easy availability of spares. Options are KTM 390, Royal Enfield 500 EFI, Honda CBR250R, Benelli TNT25 etc.

Twin Cylinder- These are a compromise between single and four-cylinder engines. Due to an additional cylinder, greater amount of power is gained summing up to 60-80 BHP. It comes at a cost of added 10-15 kg weight and adds complexity to intake, exhaust and other systems. Their availability is rare and costs more than the other two options. Very few FSAE teams opt for twin cylinder preferring the single or four cylinder engines. Options are Ninja 300R, Benelli 300 etc.

Four Cylinder- it offers the greatest amount of power, adding complexity and weight. They are able to achieve over 100 Bhp, although after the restrictor a drop of 30-35% is observed. They weigh about 30-40 kg more than the single cylinder engines and increase the estimated overall weight of the vehicle by ~15%. By splitting the power generation across four smaller cylinders, a much smoother ride is produced which is important for rider comfort. A greater number of moving parts increase the opportunity for something to go wrong. Apart from being costly, availability of its spares is low compared to single cylinders. Options are Honda CBR 600, Yamaha R6, Suzuki GXR 600, Benelli 600i, Ninja 650, etc.

		Single Cylinder		**Twin Cylinder**		**Four Cylinder**	
Decision Factor	Weight -age	Score	Value	Score	Value	Score	Value
Simplicity	10	10	100	7	70	6	60
Reliability	8	8	64	6	48	4	32
Cost	7	8	56	4	28	8	56
Power	8	7	56	8	64	8	64
Weight	6	9	54	7	42	6	36
Availability	9	8	72	6	54	3	27
Local Spares	8	9	72	7	56	5	40
Weighted Score			**474**		**362**		**315**

Table -1: Engine Selection Design Matrix

The design matrix shows that the single cylinder engine is the most suitable option for this application, mainly because of the relative simplicity. It is better to have less advanced but still functional vehicle. Vehicles are complicated and difficult to maintain; even at the FSAE competition, several teams fail events due to engine difficulty and other technical issues. By choosing a less complicated design, the engine and vehicle will have a better chance of being able to perform and last through all of the events. Though a single-cylinder provides less power, the downside is limited by the reduced weight that enables greater acceleration and handling. These properties are considerably more important than top speed in order to score well in the dynamic events of FSAE competition. However, the lower power can be mitigated by adding a turbocharger to remain competitive without drastically increasing complexity.

KTM 390 engine was chosen to further continue the research because of the following reasons which made things for team much easier: Engine to be sourced from local service center of KTM (KTM had sponsored many teams abroad and they agreed to negotiate a deal with the team too), it assured local garage support for spares and maintenance, the engine which will be procured will be a fresh unused one, it has a dry sump lubrication, the best power to weight ratio in its class, integrated cooling pump, an onboard starter and was ECU controlled which can be tuned to desired specifications.

3. REQUIRED ENGINE PERFORMANCE

The reduced mass of the single-cylinder compared to multi-cylinder engine would result in a huge reduction in the overall vehicle mass. Over the years we have seen few lightweight cars running on the single-cylinder engine configuration. The lightest vehicle until date was from UC Berkeley weighing just 123 kg (275 lbs.) in 2013 [7]. The vehicle was really basic, however was rulebook compliant and cleared all technical inspections, performing well in the event, in both dynamics as well as statics. It had a similar configuration with a 250cc single-cylinder CVT engine. This was the initiation of the new single-cylinder era in FSAE.

Fig-02: UC Berkeley 2013 Vehicle

Performance of the vehicle is described using numerous metrics, but the most widely used is the engine power. It is often misconceived that more the engine power, higher the performance. The observation mentioned below states that a vehicle with more horsepower may not necessarily be better. The data was borrowed from an Australian team (Swinburne University) which participated at that year's FSAE Australasia event. The focus is on the engine data retrieved from the Data Acquisition (DAQ) to check how effectively the engine has been used over the course of a lap [8].

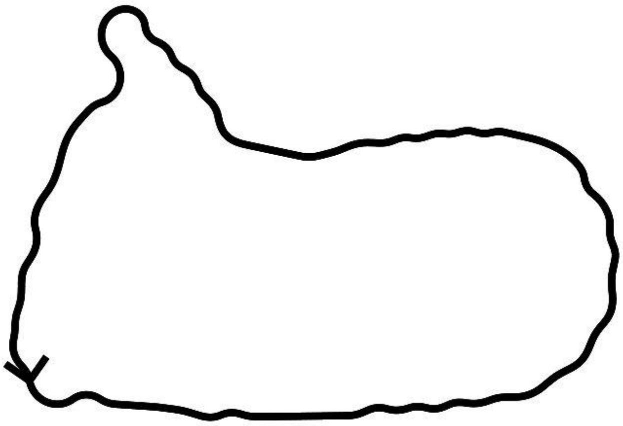

Fig-03: Track Australasia

Shown in the above figure is the typical Autocross track for FSAE events [9]. It can be seen, there aren't long straight patches. The track is extremely twisty with many slaloms and chicanes one after another. The total length of the track was 720 meters and it took roughly 60 seconds to complete it, which resulted in an average speed of about 12 m/s (43km/h). The next thing which was looked into was how the driver used the engine. The DAQ recorded the data of the throttle position sensor around the lap.

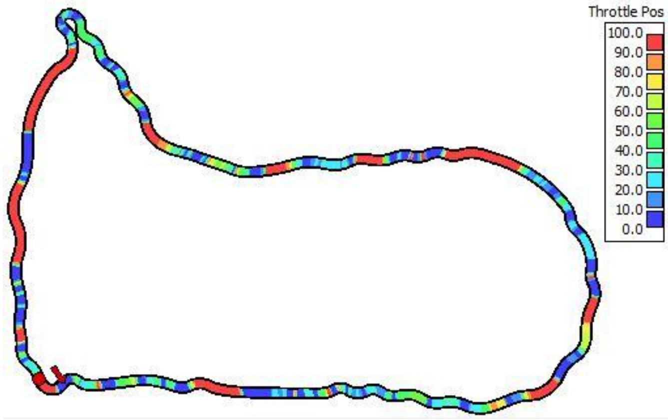

Fig-04: Track colored with Throttle Position

It was quite evident that full throttle was not used very often. Using math channels, the percentages were calculated and it was astonishing to know that the driver was on full throttle for only 15% of the lap and average throttle position was 52%. A potential conclusion from this data was that the driver is using only 50% of the engine's capability. The first thing to be considered was the non-linear throttle response. It was also researched, that the engine delivers nearly the same outputs between 80% and 100%. To understand this better a graph of percentage of max power vs. throttle position (in percentage) was plotted at a constant RPM ~8000 RPM which is the average RPM maintained by the driver.

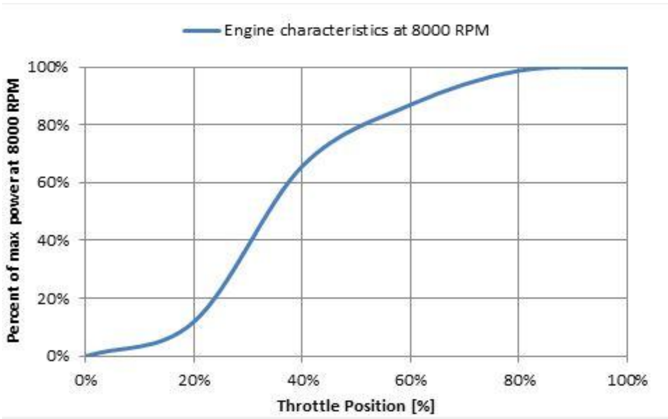

Fig-05: Engine power response to throttle position

By studying this graph a relation could be established, that changing the throttle position from 20% to 40% the power increases from 10% to 60%. Various ways are adapted for modern race vehicles to linearize the graph, but FSAE runs little restrictions on use of such methods like drive-by-wire. To have a still clear understanding of how much power was used by driver, the engine power utilized was interpolated with the track to get engine power at different parts of the track.

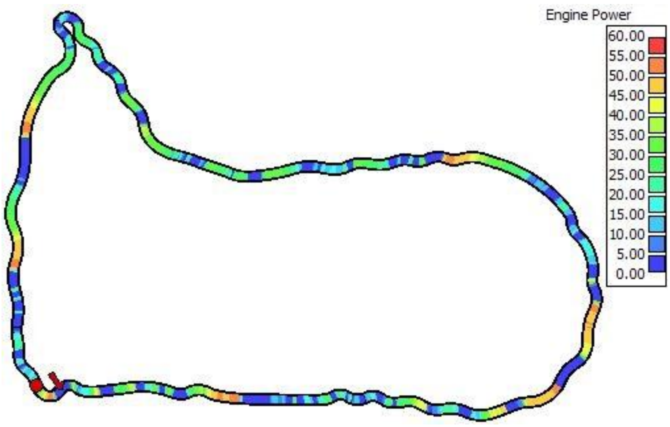

Fig-06: Engine power on Track

The area represented in the blue colors are the ones where the driver is braking or coasting through the track. In these areas, the driver is not using the engine power at all. He is using the higher potential of the engine only in a handful parts of the track. A reason of this can be understood by studying data from the DAQ for engine RPM. He generally remains in the lower end of the engine RPM range. The average engine output over the entire lap comes out to be around 27 bhp, and if the braking and coasting portions are removed, it is 34 bhp. This is just about 1/3rd of the engine capability.

A general conclusion was that the driver is rarely able to use more than 40 bhp on the track. From the above study, we can conclude that 600cc engines might perform well in Acceleration event and can have a little extra speed in Autocross and Endurance event, but since the higher power of these engines cannot be used in Autocross and Endurance event, a configuration in which the car is lighter and the single-cylinder engine is able to deliver the required power (45-55 Bhp) achieved from the above study would be more advantageous.

4. SIMULATING THE KTM 390 ENGINE

At first, the team had to come to a decision, if they want to go with the KTM Duke 390 or KTM RC 390. Both are different make of motorbikes and can have minor changes in their engines. After having preliminary talks with the manufacturing company, it was known that both engines are identically same and had the same Electronic Control Unit (ECU) irrespective of the model make or year [10]. For preparing the model of the engine to run the simulation, engine output data was necessary. So engine was procured and the Dyno test results were used to run the simulations. Two iterations were carried out, one on stock configuration and other using a standard FSAE restrictor (20 mm for Gasoline). It was seen that the loss of performance was not as significant as that in four-cylinder engines.

Other important data like the gear ratios and engine parameters were taken from the workshop manual and Homologation report received from Federation of Motor Sports Club of India (FMSCI) [11]. Using all this data a model was prepared with a total vehicle weight of 180 Kgs. This weight target was fairly achievable and further weight reductions could be carried out in coming years. It was decided to arrive at a final conclusion, if the team should go for a single-cylinder or not, using lap time simulations; because the decisions should be made on data rather than just gut feeling. The software used for same was Optimum Lap, a product of OptimumG – Vehicle Dynamics Solution, which is especially developed for FSAE teams.

These simulations use a point-mass to model the vehicle and how fast it can move along a path. Validation of the model against logged track data shows, that despite simple model the results are quite accurate. The vehicle is reduced to most fundamental components and defined in just 10 parameters [12]. It helps a lot to visualize the vehicle before even fabricating it. The only limitation to this model is it does not take into account the driver and other losses. To make the simulation more relevant FS India's track was chosen.

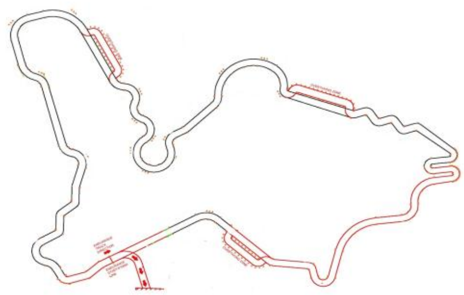

Fig-07: Formula Student India 2016 Track Map

This was the official track map as received from the organizers. The track was 4.5 meters wide and 930 meters long [9]. Simulation of two vehicles were done along this track. First vehicle was chosen from the software database which represented a four-cylinder general FSAE vehicle. Second vehicle was custom modeled as stated above to meet our specific test criteria.

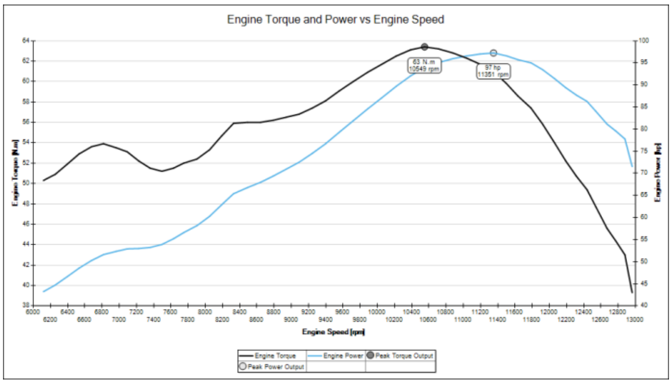

Fig-08: FSAE No Aero Engine Model

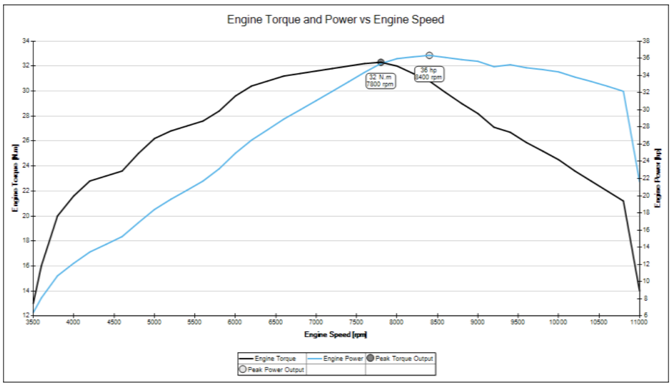

Fig-09: FSAE KTM 390 Engine Model

Here, a significant difference in both models was observed. The four-cylinder engine has more power and torque as compared to the single-cylinder engine. Moreover, one more point to observe is the engine RPM range, the four-cylinder model has its red line over 13,000 RPM whereas the rated redline for KTM 390 is around 10,500 RPM. Low-end power delivery is always beneficial as the engine does not take long to reach that RPM band and it was already discussed that the drivers do not push above 8000 RPM while driving. This is a beneficial factor while selecting the engine and KTM 390 has an advantage over the four-cylinders. Next is the comparison of the traction models for both engines.

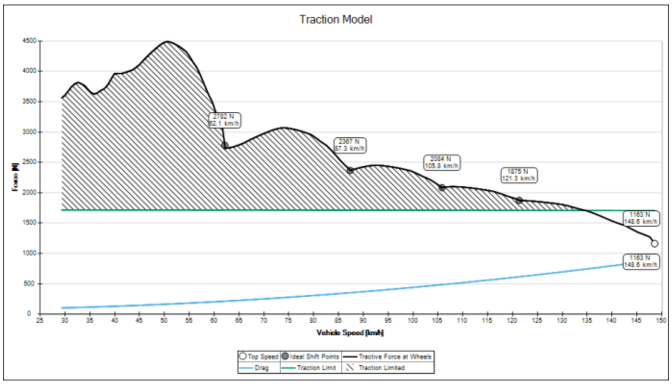

Fig-10: FSAE No Aero Traction Model

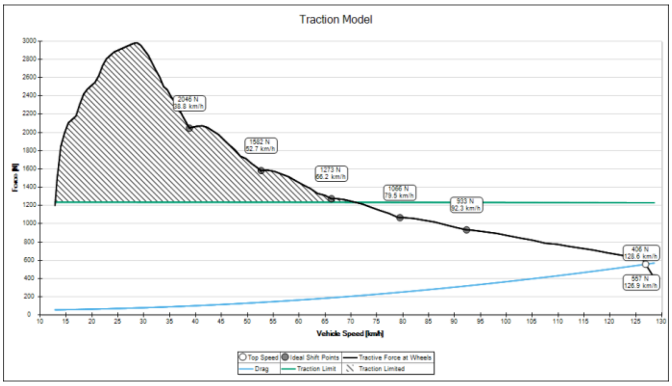

Fig-11: FSAE KTM 390 Traction Model

Studying these traction models helped to understand traction limits for both the engines with ideal shift points. The thick black line in both the graphs represents the Tractive Force at Wheels. The traction limit and tractive force produced by four-cylinder are much higher than the KTM 390 but it compensated because of the linear relation of Shift points in KTM 390. Moreover, close gear ratios mean the driver can smoothly shift between the gears without any significant Upshift Drops.

The simulation results were matching assumptions made and expectations. Single-cylinder model had a lap time of just

82 seconds which was only 2 second over the four-cylinder model which had a lap time of 80 seconds. Studying the Key Performance Index (KPI) Table from the results of the simulation concluded following facts:

-The single cylinder model was in acceleration mode on the lap for more percentage of time than the Four-Cylinder model.
-The KTM 390 model had less top speed but it carried high speeds into the corner due to less overall vehicle weight which resulted in better exit speed of the model over the other, resulting in reduced lap time.
-Fuel consumption was less in KTM 390 model.
-High no of gear shifts assured that the vehicle stays in its optimum performance range.

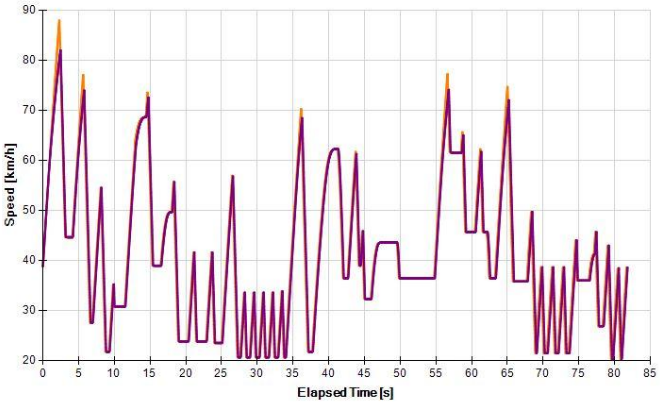

Fig-12: Simulation Graph of Speed vs. Elapsed Time

The study of above graph shows no significant difference in both models. But after careful observations, it is noted that the four-cylinder model (Orange line) had greater speed compared to the KTM 390 model (Purple Line). The peaks are tight corners on the track where the driver is braking heavily. Despite having less speed the KTM 390 model is gaining time in those corners mainly because of its less weight and high cornering ability. The graph also shows that if engine speed on track for both models are plotted, then the results would be identical.

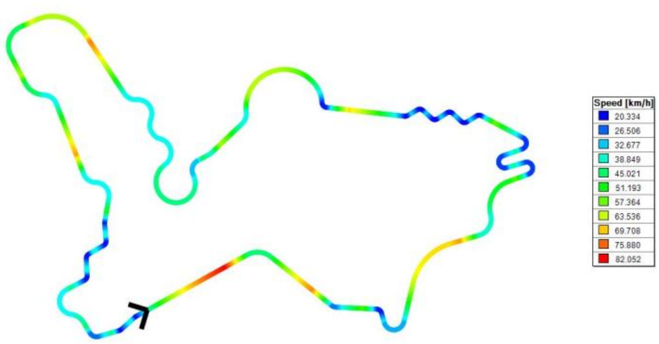

Fig-13: KTM 390 Speed on Track

5. CONCLUSIONS

After an intensive simulation project on the KTM 390cc single cylinder engine for use in Formula SAE/Formula Student, the following conclusions were reached.

Pros:

- Availability in local market is good, over hauling facilities and spares are easily available.
- Better fuel economy over the multi-cylinder engines.
- Overall vehicle weight is reduced, Center of Gravity is lowered & polar moment of inertia is decreased making the vehicle improve its braking, handling and acceleration.
- The power output of KTM 390 engine in its production state is 41 Bhp. The power drop due to restrictor is significantly less.
- Greater power output can be achieved in restricted format if a variable inlet runner and a tapered exhaust system are fitted.
- To match the performance of Four-Cylinder engines with no significant change in weight a Supercharger can be used.
- Adequate power should be available through supercharging, if used in conjunction with Bio-Ethanol Fuel.

Cons:

- Acceleration will be less as compared to Multi-Cylinder engines.
- Instant Power delivery is not possible.

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