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PHYSIOLOGICAL BASIS OF ADDICTION AND ITS CO-RELATION WITH MODALITIES FOR CURE

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Declaration

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Common notion about alcoholism is that it is a bad habit, and like all bad habits can be discarded at will. While that may be true for the casual user, alcoholism and other drug addictions were *classified as disease* several decades back by the World Health Organization(WHO). Modern imaging has proved that all addictions are rooted in an organic basis in the brain[1].That is to say, an addict's brain undergoes structural and functional changes which can be clearly demonstrated on functional MRI scans. It has been shown that Dopamine receptors start functioning abnormally and the Reward Center of the brain becomes disordered. The pre-frontal cortex, which is the seat of cognition, shrinks in size and the "Braking System" of the brain becomes dysfunctional.

The five primary brain imaging techniques – structural magnetic resonance imaging(MRI), functional MRI, magnetic resonance spectroscopy(MRS), positron emission tomography (PET), and single photon emission computed tomography(SPECT) —— reveal different aspects of brain structure or function (Table). Individually, the techniques yield knowledge of brain anatomy and tissue composition; biochemical, physiological, and functional processes; neurotransmitter activity; energy utilization and blood flow; and drug distribution and kinetics. Together and in combination with other research techniques, they inform a multidimensional understanding of the complex disease that is drug abuse and addiction[2]. Below is a chart showing the applications of modern imaging techniques.

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IMAGING TECHNIQUE	Structural magnetic resonance imaging (MRI)	Functional magnetic resonance imaging (fMRI)	Magnetic resonance spectroscopy (MRS)	Positron emission tomography (PET)	Single photon emission computed tomography (SPECT)
PRINCIPAL APPLICATIONS	Map tissue morphology, composition	Visualize changes in oxygenation and blood flow associated with brain activities	Measure cerebral metabolism, physiological processes involving specific brain chemicals; detect drug metabolites	Quantify biochemical and pharmacological processes, including glucose metabolism; drug distribution and kinetics; receptorligand interaction; enzyme targeting	Measure receptorligand interaction, physiological function, biochemical and pharmacological processes

The prefrontal cortex is the main brain region responsible for cognition. The ventral tegmental area(VTA) alongwith Nucleus accumbens are the main components of the brain's reward system. The Limbic System comprising these latter two areas alongwith amygdala and hippocampus are responsible for emotions and memories.

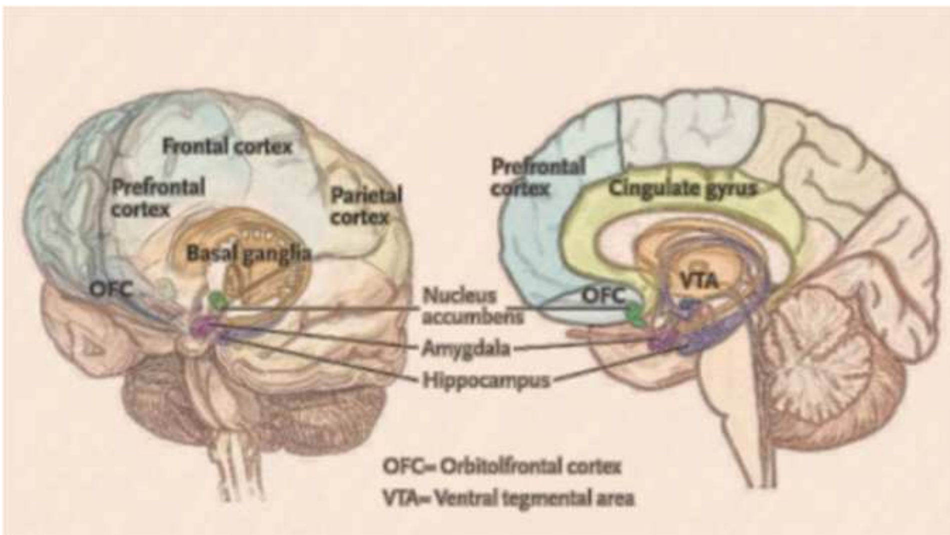
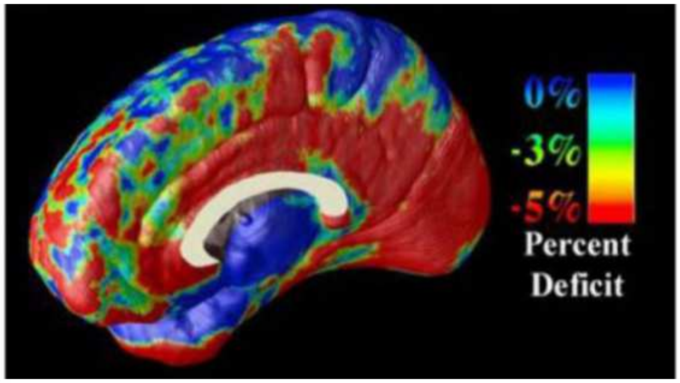


Figure 1. Major regions of the brain affected by addiction.

Structural MRI studies have demonstrated that chronic drug exposure can enlarge or shrink some areas of the brain. The frontal cortex is a brain region that supports logical thinking, goal setting, planning, and self-control. Numerous MRI studies have documented that addictive drugs cause volume and tissue composition changes in this region and that these changes are likely associated with abusers' cognitive and decision making problems. Schlaepfer and colleagues found that chronic substance abusers' frontal lobe tissues contained a lower proportion of white matter than those of matched controls[3]. Severe gray matter deficits were also found in the cingulate, limbic, and paralimbic cortices, alongwith smaller hippocampi. The hippocampus is a key site for memory storage, and the volume decrements correlated with poorer performance on a word recall test [4].

In alcoholic patients, Pfefferbaum et al[5] reported diminished cortical grey matter, most prominently in the prefrontal cortex(PFC). Few studies have shown that alcoholics' frontal cortex and other structures begin to recover their normal volumes within weeks of stopping drinking[6].

Several structural MRI studies have shown enlargement of the brain's basal ganglia in cocaine-dependent[7] and methamphetamine-dependent[8] subjects compared with healthy subjects. This is similar to enlarged basal ganglia structures seen in schizophrenic patients who have been treated with typical antipsychotic medications[9]. Because typical antipsychotics and psychostimulants both lead to occupation of dopamine receptors in the basal ganglia— the former directly and the latter indirectly, through releasing dopamine — these findings suggest the dopamine and basal ganglia structures are involved in the psychosis that occur in schizophrenia and in psychostimulant abuse.



fMRI image depicting the effects of methamphetamine on brain tissue volume

Figure 2. Brain size shrinks in chronic addictions.(Alvaro Fernandez)

Functional MRI studies have demonstrated that cocaine-addicted individuals' vulnerability to cocaine-related cues has a neurological basis, since the anterior cingulated cortex, a region associated with emotional processing , was activated on introducing cues[10]. The subjects also showed less activation in the frontal lobe. It thus appears that chronic stimulant abusers' cognitive impairments are linked to drug-related alterations in brain activation. In one study, methamphetamine dependence and poor decision making correlated with reduced activation in the PFC[11]. In another, investigators discovered that cocaine abusers had abnormally low levels of activity in midline areas of the anterior cingulate that are crucial for cognitive and behavioral control[12].

Magnetic Resonance Spectroscopy can be used to detect and measure important chemical contents within the brain. MRS scans reveal the location and concentrations of target chemicals in brain tissues. Two naturally occurring chemicals that can be studied with MRS scans are NAA(N-acetylaspartate)which gives a measure of neuronal health, and myoinositol, which is an index to the health of glial cells.

A central finding of MRS studies has been that drugs affect markers associated with inflammation , brain energy metabolism , and neuronal health. NAA concentrations were found to be reduced in basal ganglia and frontal white matter in methamphetamine abusers. This finding may explain the cognitive difficulties experienced by meth users, since NAA concentrations have correlated with measures of cognitive function even in healthy nondrug users.

Nuclear Medicine Techniques like PET and SPECT entail injecting molecules labeled with radioactive isotopes into the bloodstream. These highly sensitive techniques map the presence of specific molecules molecules in the brain. They enable researchers to study drugs' effects on key components of cell-to-cell communication, including cell receptors,transporters, and enzymes involved in the synthesis or metabolism of neurotransmitters.

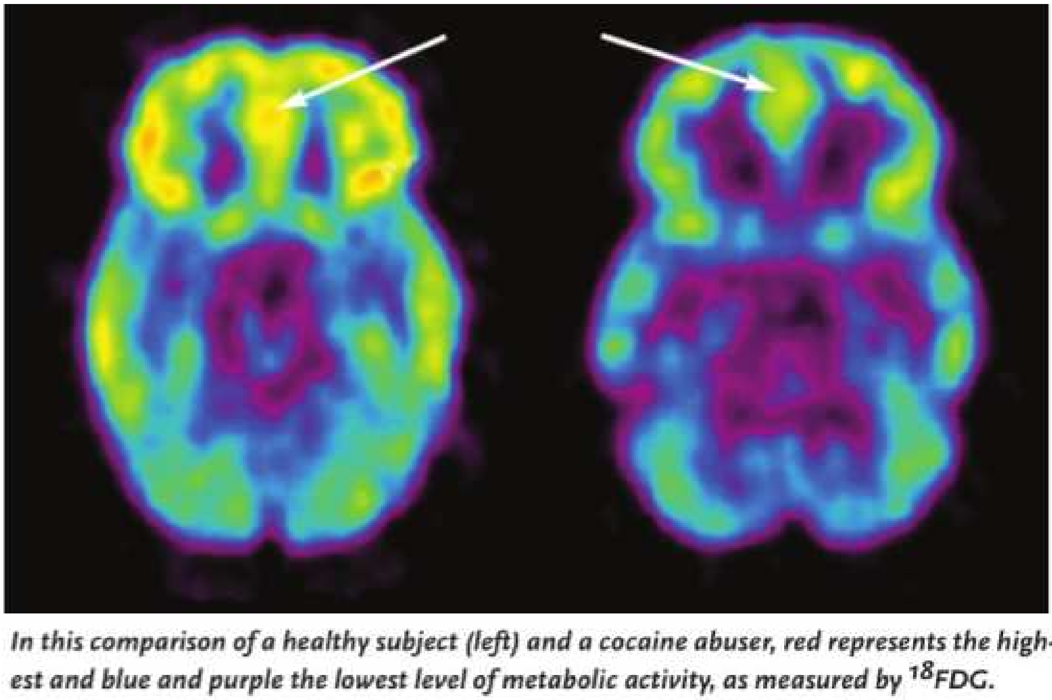


Figure 3. Cocaine abusers have reduced metabolism in the orbitofrontal cortex. (Fowler, Volkow, Kassed, Chang).

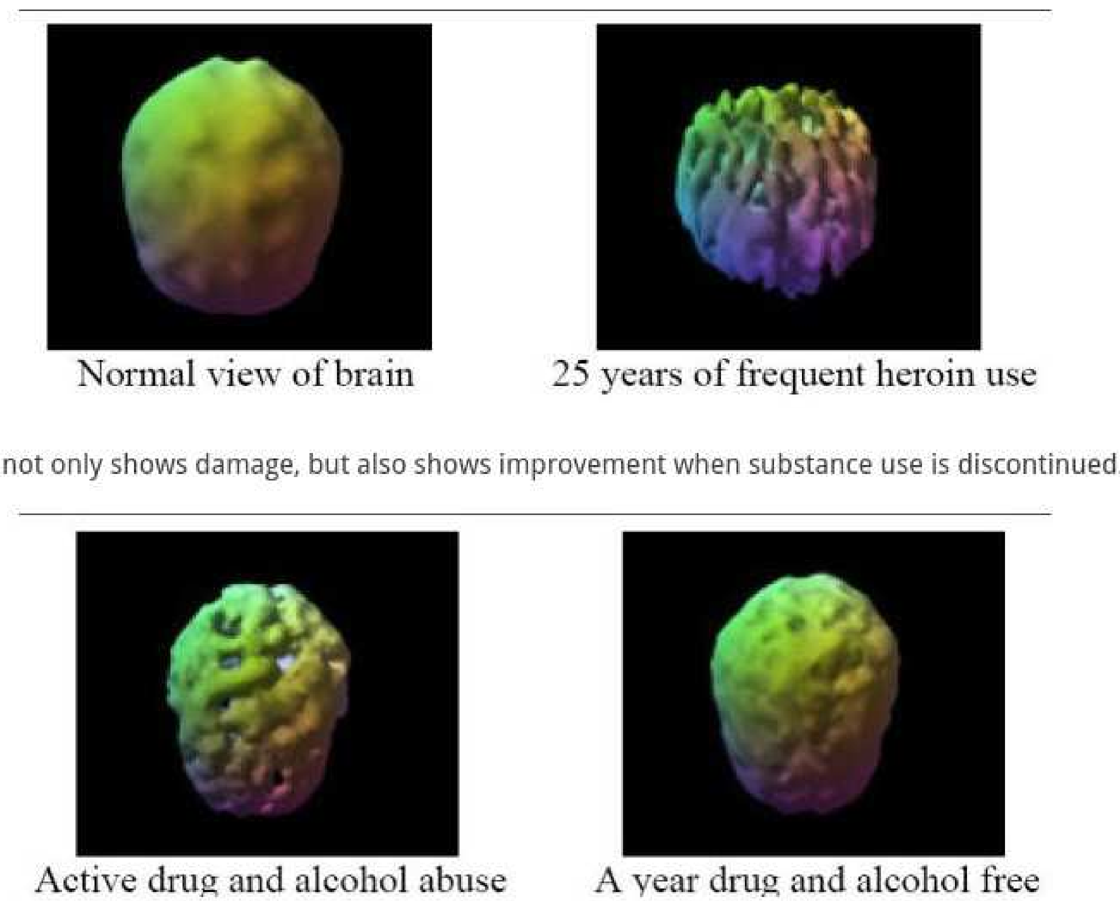
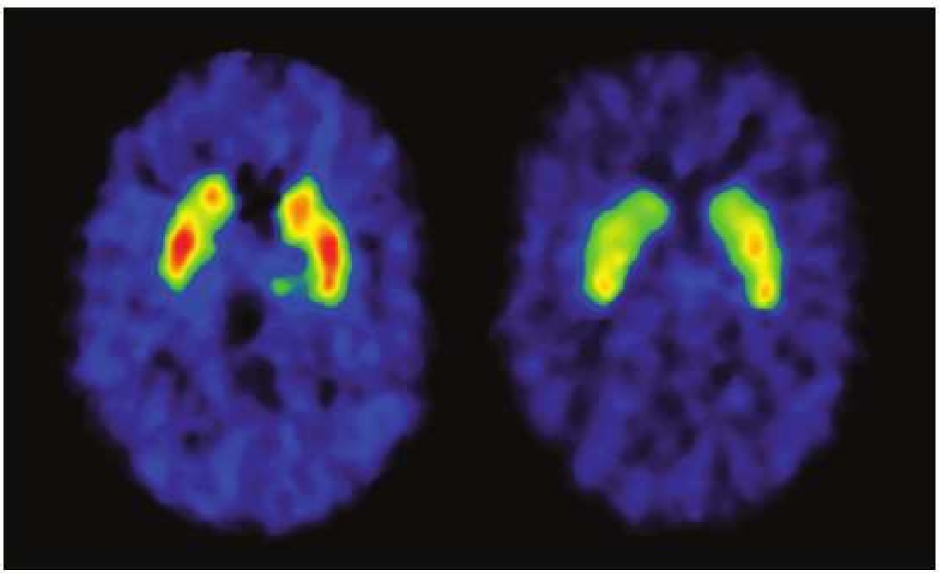


Figure 4. Changes in the size of the brain in long-standing drug and alcohol abuse.(Chris Dudley, Matt Gasperetti, Mikey Narvaez, Sarah Walorski)

The neurotransmitter Dopamine is a main determinant of how much pleasure we derive from our experiences, and is highly concentrated in the striatum, which forms part of the brain's reward system.PET studies have linked the presence and action of drugs of abuse in the brain's reward system with their euphoric properties and their ability to preoccupy addicted individuals to the exclusion of naturally rewarding activities. Also, PET and SPECT investigators established that cocaine, amphetamine, and methylphenidate, when given intravenously, produce their highs by massively increasing the amount of dopamine in the striatum.

PET studies have explored cocaine's impact on brain structures and activity, and their relationship to addicted individuals' ability to function during and after treatment. Among important results in this line, studies have shown that cocaine and methamphetamine reduce cellular activity in the orbitofrontal cortex(OFC), a brain area we rely on to make strategic, rather than impulsive, decisions. Patients with traumatic injuries to this area of the brain display problems — aggressiveness, poor judgement of future consequences, inability to inhibit inappropriate responses — that are similar to those observed in substance abusers. In a study carried out by Bolla and colleagues , abstinent cocaine users were given card games to play on a computer. Players who had used more cocaine before abstaining demonstrated less OFC activity , and they performed more poorly during the game



The striatum of the healthy control (left) is largely red, indicating the highest level of receptor availability, while that of the cocaine abuser has little red.

Figure 5. PET Brain scan showing reduced dopamine D2 receptor availability in the cocaine addicted brain.(Joanna S Fowler et al)

How do these findings co-relate with the modalities of curing an individual of addiction ?

Most treatment programs start with de-toxification[13] and medically managed withdrawal, often considered considered the first stage of treatment. Subsequent to this initial stage, drug rehabilitation treatment may be classified into the following types:

✳ Long – term residential treatment
✳ Short – term residential treatment,
✳ Outpatient treatment programs,
✳ Individualized drug counseling,

✳ Group counseling

Detoxification, the process by which the body clears itself of drugs, is designed to manage the acute and potentially dangerous physiological effects of stopping drug use. These unpleasant and potentially fatal side effects of withdrawal are often managed with medications administered by a physician in an inpatient or outpatient setting. Medications are available to assist in the withdrawal from opioids, benzodiazepines, alcohol, nicotine, barbiturates, and other sedatives. This phase of withdrawal may last from anywhere between three days and three months.

Subsequent to the detoxification, the addict is taken up for treatment by any of the modalities given above, either alone or in combination(linearly). *Long – term* residential treatment provides round the clock care usually in non-hospital settings. The best-known residential treatment model is the *therapeutic community (TC)*[14], where the addict stays as a part of a community of abstinent addicts for periods ranging from six months to two years. Addiction is viewed in the context of the individual's social and psychological deficits, and treatment focuses on developing personal accountability and responsibility as well as socially productive lives. Treatment is highly structured and can be confrontational at times, with activities designed to help residents examine damaging beliefs , self-concepts , and destructive patterns of behavior and adopt new, more harmonious and constructive ways to interact with others. Thus TCs focus on the "resocialization" of the individual, and can be modified to treat individuals with special needs, and those in the criminal justice system.

Short – term residential treatment programs provide intensive but relatively brief treatment based on a modified 12-step approach. These programs were originally designed to treat alcohol problems, but during the cocaine epidemic of the 1980s, were adapted to treat other types of substance abuse disorders. In this treatment model, a three to six week hospital-based inpatient treatment phase is followed up by extended outpatient therapy[15]. Participation in self-help groups like AA and NA is also encouraged. It is vitally important to remain engaged in aftercare programs and self-help groups on a long-term basis to reduce the risk of relapse.

Outpatient treatment programs are suitable for people having jobs and extensive social supports. These programs cost less than residential or inpatient treatments, and offer a variety of services, including intensive day treatment which can be comparable to residential programs in effectiveness, depending on the individual patient's characteristics and needs[16]. In many outpatient programs, group counseling can be a major component. Some outpatient programs are also designed to treat patients with medical or other mental health problems.

Group counseling and individual counseling focus on reducing or stopping illicit drug or alcohol use. Individual counseling, in addition, also addresses related aspects like employment status, illegal activity, and family/social relations. Through its emphasis on short-term goals, individualized counseling helps the addict develop coping strategies and tools to abstain from using drugs. Group therapy capitalizes on the social reinforcement offered by peer discussion . Research has shown that offered together, individual and group counseling achieve more positive outcomes. Motivational interviewing or confrontation also have been used with limited success[17].

Various other methods may be used in conjunction to aid in recovery. Cognitive behavior vbnm,therapy teaches a person how to recognize moods, thoughts, and situations that cause drug craving. A therapist helps the patient avoid these triggers and replace negative feelings and thoughts with ones that are healthier. Contingency management therapy involves providing incentives to a patient undergoing drug abuse treatment for staying clean. This therapy is effective in drug rehabs, but its positive effects decline when the incentives stop.

Medications have an important role to play in addiction treatment[18]. Apart from their role in detoxification and withdrawal, medications can be used to reestablish normal brain function and to prevent relapse and diminish cravings. Medication is available for opioids, tobacco and alcohol addiction, while others are being developed for stimulant and cannabis addiction. For *opioids* , methadone, buprenorphine and naltrexone are effective in suppressing withdrawal and relieving cravings. A variety of formulations exist for nicotine replacement, including patch, gum and lozenges. Bupropion and varenicline help in tobacco addiction by helping to prevent relapse. For alcohol, we have naltrexone, acamprosate and disulfiram. These medications have been found to be properly effective when used in combination with behavioral treatments and counseling.

So out of this plethora of available treatments , which is the one that will work the best ? Though no easy answers are available, we can come to some conclusions based on the studies carried on brain imaging regarding neuronal structural and functional abnormalities detected in the addicted brain, and on the experiences gained first-hand in the results obtained from the various treatment modalities over the past five-six decades. The brain imaging can be summed up by the findings of Dr.Nora Volkow, Director of the NIDA (National Institute of Drug Addiction, USA), who has been using PET scans to record trademark characteristics in the brains of chronic drug users since 1985. These included blood flow, dopamine levels and glucose metabolism – a measure of how much energy is being used and where (and therefore a stand-in for figuring out which cells are at work). Volkow and colleagues found decreased blood flow to the prefrontal cortex of cocaine users, that continued after 10 days of withdrawal from cocaine use[19]. After the subjects had been abstinent for a year, Volkow rescanned their brains and found that they had begun to return to their predrug state.

Further, Volkow observes, "The changes induced by addiction do not just involve one system; there are some areas in which the changes persist even after two years". One area of delayed rebound involves *learning.* Somehow in methamphetamine abusers, the ability to learn new things remained affected after 14 months of abstinence. If the kind of damage that lingers in an addict's learning abilities also hangs on in behavioral areas, this could explain why rehabilitation programs that rely on cognitive therapy – teaching new ways to think about the need for a substance and the consequences of using it— may not always be effective, especially in the first weeks and months after getting clean. "Therapy is a learning process," notes Dr. Frank Vocci [20], director of pharmacotherapies at NIDA. *"We are trying to get addicts to change cognition and behavior at a time when they are least able to do so."*

The clear conclusion that we can draw from these extensive studies over past thirty years, is that the addict requires a minimum of *three months to start recovering* from the disease of addiction. If the patient is able to pass this initial period of three months by behavioral , self-help ,outpatient treatments, so much the better. But if repeated attempts to stay clean for 3-4 months do not work out, then residential programs ought to be utilized. The total duration of stay in the rehabilitation centres will vary from case to case, but the best approach seems to be to utilize the first three months to inculcate basic rules of discipline and hygiene in a strictly regimented programme which is the basis of TC. Thereafter, we may expect the abstinent addict to start developing the ability to understand what is explained in classes about the nature of addiction and its consequences. It is at this stage that the various other aspects of the dysfunctional addict's life, including social, emotional, and behavioral delinquencies may be tackled in a structured fashion, as is carried out in TC programmes. Social and creative skills can be developed through various techniques, alongwith the assumption of some responsibility. It is only when the subject starts finding pleasure in various mundane activities like dancing, music , reading, cooking, artwork and the like, *without* the use of the drug that we can start expecting a positive outcome from the treatment.

To sum up, it is safe to conclude that the duration of stay in a rehab should be a minimum of three months, going upto a year or more. Definitely, some addicts require multiple stints in rehab before a cure is effected, as is evident from the membership of AA and NA ; but the message of attending meetings of AA and NA after discharge from the rehab should be re-inforced while in the rehab. *The message of AA and NA* is clear – no one can better understand and thereby better help an addict, than a recovered addict. Hence the importance of recovered addicts as helpers and councillors in rehab centres.

They are best suited to assess the quality of recovery of the inmate , the specific therapy required to enhance this recovery, and the time required to be spent in the rehab to achieve optimum result.

Following the initial 3-6 months of total abstinence, continued therapy by the peer group seems to be essential to maintain sobriety and recovery. This reinforcement by attending meetings and sessions of self-help groups like AA and NA on a *life-long* basis seems to be vital to maintain recovery and prevent relapse.

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ANATOMY OF TRIGEMINAL NERVE: A REVIEW

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Declaration

The Declaration of the author for publication of Research Paper in The Indian Journal of Research Anvikshiki ISSN 0973-9777 Bi-monthly International Journal of all Research: I, *Amit Kumar Singh* the author of the research paper entitled ANATOMY OF TRIGEMINAL NERVE: A REVIEW declare that , I take the responsibility of the content and material of my paper as I myself have written it and also have read the manuscript of my paper carefully. Also, I hereby give my consent to publish my paper in Anvikshiki journal , This research paper is my original work and no part of it or it's similar version is published or has been sent for publication anywhere else. I authorise the Editorial Board of the Journal to modify and edit the manuscript. I also give my consent to the Editor of Anvikshiki Journal to own the copyright of my research paper.

Abstract

The trigeminal nerve, fifth equal of cranial nerves, a mixed nerve is considered by possessing motor and sensitive components. The sensitive portion takes to the Nervous System Central information from the skin and mucous membrane of great area of the face, being responsible also for a neural disease, known as the Trigeminal Neuralgia. So anatomy is very important for purpose of diagnosis and treatment of neuralgia and for application of local anaesthesia to perform minor procedure of face.

Trigeminal nerve or fifth cranial nerve is not only the most important nerve of the middle cranial fossa, but also the largest of all cranial nerves. It is especially important clinically because of its involvement in major trigeminal neuralgia or tic douloureux, an accepted treatment of which is section of the sensory root of the fifth nerve, most commonly carried out through the middle cranial fossa.

Unlike many other cranial nerves it is a mixed cranial nerve carrying mainly sensory and partly motor from the oro-maxillofacial region. General somatic afferent fibers convey both exteroceptive and propreoceptive impulses. Exteroceptive impulses of touch, pain, and thermal senses are transmitted from the skin of the face and forehead, mucous membranes of the nasal cavities, oral cavities, nasal sinuses, and floor of the mouth; the teeth; the anterior two thirds of the tongue; and extensive portion of the cranial dura. Propreoceptive impulses (deep pressure and kinesthesis) are conveyed from the teeth, periodontium, hard palate, and temperomandibular joint receptors. The nerve is also involved in conveying afferent fibers from stretch receptors in the muscles of mastication. The special visceral

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efferent fibers innervate the muscles of mastication, the tensor veli palatini muscles, muscles of the eye, and facial muscles.

The trigeminal nerve is attached to the lateral part of the pons by its two roots, motor and sensory. The large sensory root (portio major) and the small motor and propreoceptive root (portio minor) of the fifth nerve arise from the lateral pontine region where the fibers pass through the brachium pontis. It is the sensory root that bears the large semilunar or gasserian ganglion, the equivalent of dorsal root ganglion of the spinal nerve, from which the three great branches of the nerve arises; the portio minor blends neither with the sensory root nor with the ganglion, but passes through the foramen ovale with the mandibular branch from the ganglion, and joins this branch just outside the foramen.

Semilunar Ganglion

The semilunar ganglion is developed from the neural crest. Like the spinal ganglia it contains unipolar neurons. It is located in meckel's cave. The ganglion is crescent shaped.

The ganglion with its unipolar neurons forms central and peripheral processes. The peripheral branches form the ophthalmic, maxillary and mandibular divisions of the nerve. The central branches are the sensory roots of the trigeminal nerve. These central branches leave the semilunar ganglion and pass back and enter the pons, where it divides into ascending and descending fibers. The ascending fibers terminate in the upper sensory nucleus in the pons lateral to the motor nucleus. The upper nucleus is the sensory nucleus of the trigeminal nerve; it gives rise dorsal trigeminothalamic tract. The sensory fiber of this tract ascends upwards. Most fibers cross the opposite side and accompany the medial lemniscus to the thalamus.

The spinal (bulbospinal) nucleus of the trigeminal nerve gives rise to the ventral trigeminothalamic tract. The spinal nucleus extends caudally from the main sensory nucleus to the second cervical segment. The fibers of the ventral trigeminothalamic tract cross to the opposite side and ascend to the thalamus. They form a loosely arranged bundle in the medial lemniscus. From the thalamus these fibers continue on to the cerebral cortex. These fibers convey pain and temperature from the entire trigeminal area.

The cells of the semilunar ganglion give rise to the fibers of general sensation which form the ophthalmic and maxillary branches of the nerve, and the major portion of the mixed mandibular nerve; these are distributed peripherally to skin and mucous membrane of the head and neck, they form the portio major. The portio minor supplies voluntary motor and propreoceptive fibers to the muscles of mastication and a few others derived from the mandibular arch.

It may be remembered that while the fifth nerve in its peripheral distribution is intimately connected with all four of the larger parasympathetic ganglia in the head, it does not contain any preganglionic fibers for these ganglia. Similarly although the lingual branch contains fibers for taste buds of anterior two third of the tongue, these fibers don't enter the brain stem with the fifth nerve, but are rather seventh nerve fibers.

Although the fifth nerve arises in the posterior cranial fossa, its roots extend anterolaterally and cross the petrous pyramid, so that the ganglion lies in the middle cranial fossa, on the sloping anterolateral surface of the petrous pyramid.

Trigeminal (meckel's) cave

The relation ship of the roots and ganglion of the fifth nerve to the arachnoid dura is of importance in the surgical approach to the ganglion and its sensory root. Within the posterior cranial fossa the motor and sensory roots of the ganglion passes freely through the large sub-arachnoid space, but as they cross the petrous ridge they enter the dura , which at this point is evaginated to enclose a foreman through which the roots pass from the posterior to the middle cranial fossa. This evagination of the dura is continued about the ganglion itself, and the space enclosed between the two dural layers is known as the trigeminal or meckel‘s cave

Division of the trigeminal nerve

Three large nerves proceed from the convex border of the semilunar ganglion;

- ✳ Ophthalmic nerve V1
- ✳ Maxillary nerve V2
- ✳ Mandibular nerve V3

From the ganglion the peripheral branches of the fifth nerve make their exit through three separate foramina of the skull.

Ophthalmic nerve

The ophthalmic division is the smallest of the three branches of the semilunar ganglion. It leaves the anterior medial part of the ganglion and passes forward in the lateral wall of the cavernous sinus, between the maxillary nerve below and the trochlear and oculomotor nerves above; just before it enters the superior orbital fissure the ophthalmic nerve divides into three main branches;

1) Lacrimal
2) Frontal
3) Nasociliary

The Nasociliary usually being the first to be given off and reminder of the nerve then dividing to form the frontal and lacriminal

All three of these branches then enter the orbit through the superior orbital fissure, but the frontal and the lacriminal branches do so above the common annular tendon and thus lie outside of the muscle cone, while the nasociliary passes through the so called oculomotor foramen within the annulus of Zinn.

Area of supply

- ✳ Its fibers are sensory, or afferent, from
  - ♦ The scalp,
  - ♦ The skin of the forehead,
  - ♦ The upper eyelid lining the frontal sinus,
  - ♦ The conjunctiva of the eyeball,
  - ♦ The lacriminal gland
  - ♦ The skin of the lateral angle of the eye.
- ✳ It also transmits sensory impulses from the sclera of the eye ball and the lining of the ethmoidal cells.
- ✳ In the middle cranial fossa, the nervus tentorii branches from the ophthalmic division to supply the dura

✳ The ophthalmic division also gives off communication branches to the oculomotor, trochlear and abducent cranial nerves

i) Lacrimal nerve: This is the smallest of the three branches. It passes through the superior orbital fissure above the lateral rectus muscle and its position lies lateral to the frontal and trochlear nerves and above and medial to the ophthalmic vein it runs along the lateral or upper border of the lateral rectus muscle, and in the distal two thirds of this course is joined by the lacriminal artery, the two running together to reach the lacriminal gland. The nerve continues beyond the gland to supply the conjunctiva and usually the skin of the lateral corner of the eyelids, where it anastomosis with the branches of zygomaticofacial nerve.

Through the anastomosis, which the lacrimal nerve receives from the zygomaticotemporal branch of maxillary nerve, before leaving the orbit, the lacrimal nerve receives secretory fibers for the supply of the lacriminal gland

ii) Frontal nerve: The frontal nerve the largest branch of the ophthalmic nerve enters the orbit through the superior orbital fissure above the lateral rectus muscle where it lies between the trochlear and the lacrimal nerves. The nerve passes as a direct continuation of the ophthalmic division above the lavator palpebrae, and close to the roof of the orbit, to divide in to its two terminal branches, 1) Supratrochlear nerve, 2) Supraorbital nerve:

Supratrochlear nerve: Supratrochlear nerve passes more medially towards the medial angle of the orbit; it passes above the trochlear of the superior oblique muscle where it usually communicates with the infratrochlear nerve, and pierces the orbital septum with the frontal artery to curve upwards with the facial artery and supply the skin and conjunctiva of the upper eyelid.

Supraorbital nerve: The supraorbital nerve is the larger of the two branches of frontal nerve, continues the direction of the frontal nerve to pass through the supraorbital notch and be distributed to the skin of the forehead and of the upper eyelid. As it passes through the supra-orbital notch it supplies a twig to the frontal sinus through the aperture for the diploic vein in the notch.

The supraorbital nerve may divide into two branches before it crosses the orbital rim, in which case the branches are called

a. Supra-orbital nerve.
b. Frontal nerve.

At there points of exit from the orbit both supraorbital and Supratrochlear nerves lie deep to the orbicularis and frontalis muscles, and there terminal cutaneous branches pierce these muscles.

iii) Nasociliary nerve: The nasociliary nerve arises from the medial and inferior portion of the ophthalmic; it is intermediate in size and is usually the first of the three branches to be given off. It enters the orbit within the annulus of Zinn, being there fore only branch of the ophthalmic to lie with in the muscle cone.

Upon entering the orbit it lies lateral and superior to the optic nerve, and in this position is associated with the ophthalmic artery.

The branches of the nasociliary nerve are divided into those arising in the orbit, in the nasal cavity and on the face.

a. Branches in the orbit

1. Long root of the ciliary ganglion; Arising from the nasociliary nerve contains sensory fibers, which pass through the ganglion without synapsing and continue on to the eyeball by means of short ciliary nerves.

2. Long ciliary nerve; There are usually 2-3 long ciliary nerves branching from nasociliary nerve. They are distributed to iris and the cornea. In addition the long ciliary nerve also contains postganglionic fibers, from the superior cervical sympathetic ganglion.

3. Posterior ethmoidal nerve; Enters the posterior ethmoidal canal and distributed to the mucous membrane lining the posterior ethmoidal cells and the sphenoid sinus.

4. Anterior ethmoidal nerve; The anterior ethmoidal nerve continues along the medial wall of the orbit. In its course it gives off filaments that supply mucous membrane of the anterior ethmoidal cells and frontal sinus. In the upper part of the nasal cavity, the ethmoidal nerve divides into two sets of anterior nasal branches, the internal and external nasal branches.

a. Internal nasal branches: It in turn divide in the upper anterior part of the nasal cavity in two

- ♦ Medial or septal branches
- ♦ Lateral nasal branches

b. External nasal branches: passes externally to supply the skin over the tip of the nose and the skin over the ala of the nose.

b. Branches arising in the nasal cavity: They supply the nasal mucosa.

c. Terminal branches on the face: The terminal branches course below the trochlear nerve to supply sensory fibers to the skin of the medial parts of the both eyelids, the lacriminal sac and the lacrimal caruncle.

Maxillary nerve

The maxillary division of the trigeminal nerve is purely sensory in function. The maxillary nerve originates at the middle of the semilunar ganglion and continues forward in the lower part of the cavernous sinus. It then passes to the foramen rotundum, through which it leaves the cranial fossa and enters the pterygopalatine fossa. It enters the inferior orbital fissure to pass in to the orbital cavity. Here it turns laterally in a groove on the orbital surface of the maxilla, called the infra orbital groove. Continuing forward, the second division emerges on the anterior surface of the maxilla through the infraorbital foramen, where it divides.

In its course from the semilunar ganglion, the maxillary division gives off branches in four regions:

1. In the middle cranial fossa.
2. In the pterygopalatine fossa
3. In the infraorbital groove and canal
4. On the face.

I. Branches given off in the middle cranial fossa; In the middle cranial fossa a small branch, the middle meningeal nerve, passes with the middle meningeal artery and its branches to supply the dura with the sensory fibers.

II. Branches in the pterygopalatine fossa:

A) Zygomatic nerve. The zygomatic nerve leaves the second division in the pterygopalatine fossa and passes anteriorly and laterally through the inferior orbital fissure in to the orbit. Here it divides in to two parts zygomaticofacial and zygomaticotemporal nerves.

i) Zygomaticofacial nerve: Zygomaticofacial nerve passes forward on the lateral orbital foramen, pierces the orbicularis oculii muscle and supplies sensory fibers to the skin over the prominence of the zygomatic bone.

ii) Zygomaticotemporal nerve: Zygomaticotemporal nerve leaves the orbit between the greater wing of the sphenoid and the zygomatic bone to enter the temporal fossa.

B) Pterygopalatine (sphenopalatine) nerve: Pterygopalatine (sphenopalatine) nerve is two short nerve trunks that unite at the pterygopalatine ganglion and are then redistributed in to several branches. The nerve serves as important functional communications between the ganglion and the maxillary nerve.

The branches of distribution of the pterygopalatine nerves are divided in to three groups: orbital, nasal and palatine.

1. Orbital branches. They are 2-3 fine filaments that enter the orbit through the inferior orbital fissure and supply the periosteum of the orbit and the mucous membrane of part of the ethmoidal cells and the sphenoid sinus.

***2.** Nasal branches*: They are in turn divided in to two

i. *Posterior superior lateral nasal branches*
ii. Medial and septal branches

3. Palatine branches: they descend in the pterygopalatine canal where it usually divides in to three strands

i. Greater or anterior palatine nerve: Emerges out of greater palatine foramen in hard palate and courses anteriorly to supply major part of the hard palate and the palatine gingivae.
ii. *Middle palatine nerve:* Emerges out of lesser palatine foramen and supplies soft palate.
iii. *Posterior palatine fibers:* Emerges out of lesser palatine foramen and supplies tonsil.

C). Posterior superior alveolar branches: 2-3 branches leave the maxillary division just before it enters the inferior orbital fissure. They pass downward and continue on the posterior surface of the maxilla. It gives off sensory fibers to the mucous membrane of the maxillary sinus. It then supplies the maxillary molars and their gingivae.

III. Branches in the infraorbital groove and canal: Here the nerve is known usually as infraorbital nerve. It gives off several fiber groups mainly known as two nerves

1. Middle superior alveolar nerve
2. Anterior superior alveolar nerve

Middle superior alveolar nerve: It descends down from the canal and supplies the bicuspids. Forms superior dental plexus.
Anterior superior alveolar nerve: Descends down in the anterior part of the canal to supply the maxillary incisors and cuspids.
III. Terminal branches of the maxillary nerve on the face: As the infra orbital nerve emerges out of the foramen it gives out three terminal branches.

i. Inferior palpebral branches.
ii. External or lateral nasal branches
iii. Superior labial branches.

Mandibular nerve

The mandibular nerve, as it leaves the skull through the foramen ovale, consists of two rootlets, a large laterally lying sensory one which contains fibers derived from semilunar ganglion, and medial motor root which is the continuation of the portio minor of the nerve, and is much smaller. As these two parts emerge through the foramen ovale in intimate contact they unite to form the mandibular nerve. In this position the otic ganglion lies on the medial side of the nerve, between it and the tensor muscle

Most of the muscular branches of the nerve leave it at its anterior border, while its larger sensory branches are from the posterior part of the nerve; it is frequently described, therefore, as forming two divisions, an anterior a mixed motor and sensory one, and a posterior, largely sensory one. This division is not, however, very obvious.

Based on this distribution of the nerve; the mandibular division may be divided into following groups.

I. Branches from the undivided nerve:

a). Nervus spinosus; Arises outside the skull and then passes into the middle cranial fossa to supply the dura and the mastoid cells.

b). Nerve to internal pterygoid muscle; A branch of the motor root passes to innervate the internal pterygoid muscle, the tensor veli palatine and the tensor tympani muscles.

II. Branches from the divided nerve:

A) Anterior division; Anterior division is smaller than the posterior division. It supplies muscles of mastication, the skin and mucous membrane of the cheek, and the buccal gingivae.

i) *Pterygoid nerve.* The nerve enters the medial side of the external pterygoid muscle to provide its motor nerve supply.

ii) *Masseter nerve.* Passes above the external pterygoid to transverse the mandibular notch and enter the deep side of the masseter muscle.

iii) *Nerve to the temporal muscle.* ♦ Anterior deep temporal nerve, ♦ Posterior deep temporal nerve

iv) *Buccal nerve.* Usually the buccal nerve passes downwards, anteriorly and laterally between the two heads of the external pterygoid muscle. At above the level of the occlusal plane of the mandibular second and third molars, it divides into several branches that ramify on the buccinator muscle it then sends fibers to the mucous membrane of the cheek region and skin of the cheek. The buccal nerve supplies almost entire mucosa of the cheek.

B) Posterior division: The larger posterior division is mainly sensory but also carries some motor components.

1) Auriculotemporal nerve: The Auriculotemporal nerve arises by a medial and a lateral root. These roots embrace the middle meningeal artery and unite behind the artery just below the foramen spinosum. The united nerve passes posteriorly, deep to the external pterygoid muscle, and then between the sphenomandibular ligament and the head of the condyle of the mandible. It passes with the superficial temporal artery in its upward course and divides into numerous branches.

Branches of auriculotemporal nerve;

i) Parotid branches: As the auriculotemporal nerve passes the parotid gland, it gives off sensory, secretory, and vasomotor fibers to the gland.

ii) Articular branches: One or two twigs of sensory fibers pass from the auriculotemporal nerve and enter the posterior part of the temporomandibular joint.

iii) Auricular branch: These are sensory fibers supplying the helix and tragus.

iv) Meatal branches: Two branches usually supply the skin lining the meatus and the tympanic membrane.

v) Terminal branches: supply the scalp over the temporal region.

2) Lingual nerve: Smallest among the branches of the posterior division of the mandibular nerve. At first it passes medially to the external pterygoid muscle and, as it descends, lies between the internal pterygoid muscle and the ramus of the mandible in the pterygomandibular space

In the pterygomandibular space the lingual nerve lies parallel to the inferior alveolar nerve but medial and anterior to it. It then passes deep to reach the side of the base of the tongue. At the side of the tongue it lies below the lateral lingual sulcus.

The lingual nerve contributes many sensory fibers to the mucous membrane of the floor of the mouth and gingivae on the lingual surface of the mandible.Lingual nerve carries fibers of chorda tympani nerve from the facial nerve.

3) Inferior alveolar nerve. The inferior alveolar nerve is the largest of the branches of the posterior division of the mandibular part of the trigeminal nerve. It passes downwards on the medial of the external pterygoid muscle and the medial side of the mandibular ramus. On the medial side of the ramus the nerve enters the mandibular foramen. Within the mandibular canal it gives off branches to the mandibular teeth as apical fibers that enters the apical foramina of the teeth to supply the dental pulp.

As the inferior alveolar nerve reaches the mental foramen, it divides in to two terminal branches

- The mental nerve: leaves out of the mental foramen to supply the skin of the chin and lower lip
- The incisive branch: continues with in the canal to supply the anterior teeth by forming the incisive plexus.

Before entering the mandibular foramen inferior alveolar nerve gives off a branch, the mylohyoid nerve, which contains sensory and motor fibers. It continues downwards in the mylohyoid groove of the mandible and passes forward below the mylohyoid muscle, to which it sends motor fibers, and it supplies motor fibers to the anterior belly of digastric.

Conclusion

Trigeminal neuralgia is the important condition commonly associated with the fifth nerve. The cause or causes of major trigeminal neuralgia (tic douloureux) are not understood. It is widely believed that the precipitating cause may lie within the central nervous system. The concept that pressure upon the nerve root may be the cause of many cases of trigeminal neuralgia.

Regardless of the ultimate causative factor of trigeminal neuralgia, the attacks may be alleviated or abolished by interruption of pain fibers in the nerve. This has been attempted by injecting alcohol to the ganglion, extirpating the ganglion, sectioning the sensory root and section of the pain fibers as they course caudally in the medulla. Of these sectioning of the root is more favored.

In surgeon's point of view, approach to the root needs a sound knowledge of the anatomy of the area. The frequently approached method to the trigeminal ganglion is temporal approach to the sensory root.

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ELECTRIFIED HYBRID VEHICLES STATE OF CURRENT TECHNOLOGY, CHALLENGES AND FUTURE DEVELOPMENTS

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Declaration

The Declaration of the author for publication of Research Paper in The Indian Journal of Research Anvikshiki ISSN 0973-9777 Bi-monthly International Journal of all Research: I, *Gaurav Bali* the author of the research paper entitled ELECTRIFIED HYBRID VEHICLES; STATE OF CURRENT TECHNOLOGY, CHALLENGES AND FUTURE DEVELOPMENTS declare that , I take the responsibility of the content and material of my paper as I myself have written it and also have read the manuscript of my paper carefully. Also, I hereby give my consent to publish my paper in Anvikshiki journal , This research paper is my original work and no part of it or it's similar version is published or has been sent for publication anywhere else. I authorise the Editorial Board of the Journal to modify and edit the manuscript. I also give my consent to the Editor of Anvikshiki Journal to own the copyright of my research paper.

Abstract

This paper provides a brief introduction to the hybrid vehicles and various architectures found in production hybrid electric vehicles (HEVs). This is followed by a comprehensive overview of the various electrical and electronic components of the hybrid powertrain. This section looks at electric machines, energy storage systems (ESS), battery management systems (BMS), inverter/motor controller and DC-DC converters typically used in HEV and PHEV applications. A discussion about advantages and drawbacks of available choices for those components is presented, supplemented with comments on state-of-art choices and illustrated with examples of production vehicles. This is succeeded by discussions on the current challenges in ICE-Electric hybrids, regarding aspects of batteries, power electronics, controls and regenerative braking. Finally, the paper concludes with a section showcasing the latest technologies which present promising potential and are currently under development.

Introduction

Carbon dioxide emissions from transportation amount to over a fifth of total global emissions, according to the International Energy Agency[1]. In the EU, CO2 emissions from road transport increased by almost 23% between 1990 and 2010. Transport is the only major sector in the EU where greenhouse gas emissions are still rising. Recent EU legislation has set binding emission targets on manufacturers for new car and van fleets; these must not emit more than an average of 130gCO2.km^{-1} by 2015 and

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95gCO2.km^{-1}by 2020. This compares with an average of almost 160g in 2007 and 135.7g in 2011[2].

With growing concerns about global warming, increasingly stringent regulations on emissions and fuel economy, and tightened constraints on energy resources, hybrid electric vehicles are attracting ever more attention from vehicle manufacturers, governments, and customers. The greater fuel economy and lower emissions of hybrids over internal combustion engine vehicles is achieved by relying on a smaller sized engine for average usage, whilst making use of both the engine and the electric motors for peak power needs. Battery storage capacity is available to store and reuse recaptured energy from regenerative braking, especially in stop-and-go traffic typical of a city drive-cycle.

The first truly hybrid electric vehicle is often credited to the designer Ferdinand Porsche, with his Lohner-Porsche Elektromobil, which made a debut at the 1900 Paris Exposition. Initially a purely electric vehicle, it was soon complemented by an additional internal combustion engine to recharge the batteries. However, hybrid-electric vehicles did not become widely available until the release of the Toyota Prius in 1997, followed by the Honda Insight in 1999. As of December 2013, over 7 million hybrid electric vehicles have been sold worldwide, led by Toyota with more than 6 million hybrids sold, and followed by Honda and Ford [3]. They now form a core segment of the automotive market. Research and development efforts have been focused on developing novel concepts, low-cost systems, and reliable hybrid electric powertrains.

Current State of Technology in Hybrid Vehicles

1. Hybridarchitectures

To serve the diverse and segmented market of automobiles, as reflected by conventional passenger vehicles ranging from five-seater family saloons and estate wagons to two-seater supercars, there are multiple recipes for a good vehicle depending on its purpose. To account for this variation, three main architectures exist in hybrid electric vehicles (HEVs) – Series, Parallel and Power-Split.

Before discussing architectures, it is useful to take note of the '*Hybridization Ratio*'. It measures the 'extent of hybridization' and is mathematically given by :

$$Hybridization\ Ratio = \frac{Power\ of\ Motor\ Generator}{Power\ of\ Motor\ Generator + IC\ Engines}$$

T A B L E 1 A *Series Hybrid Electric Vehicle Layout (Rear-Wheel Drive) [Adapted from Barcaro M.]*

	Micro	Mild	Full	Plug-In
Hybridization Ratio	**<4%**	**4-20%**	**20-40%**	**>40%**
Power (kW)	2-5	10-20	30-50	50+
Voltage Level (V)	12	100-200	200-300	300+
Energy Savings (%)	5-10	20-30	30-50	50+
Price Increase (%)	3	20-30	30-40	40+

Micro **Mild** **Full** **Plug-In**

1.1 Series Hybrid

Series architecture is characterized by the electric motor delivering the tractive power[1]. The main components are a downsized Internal Combustion Engine (ICE), a generator, a battery pack, inverter/ motor controller and a motor, interfaced using High Voltage (HV) power electronics.

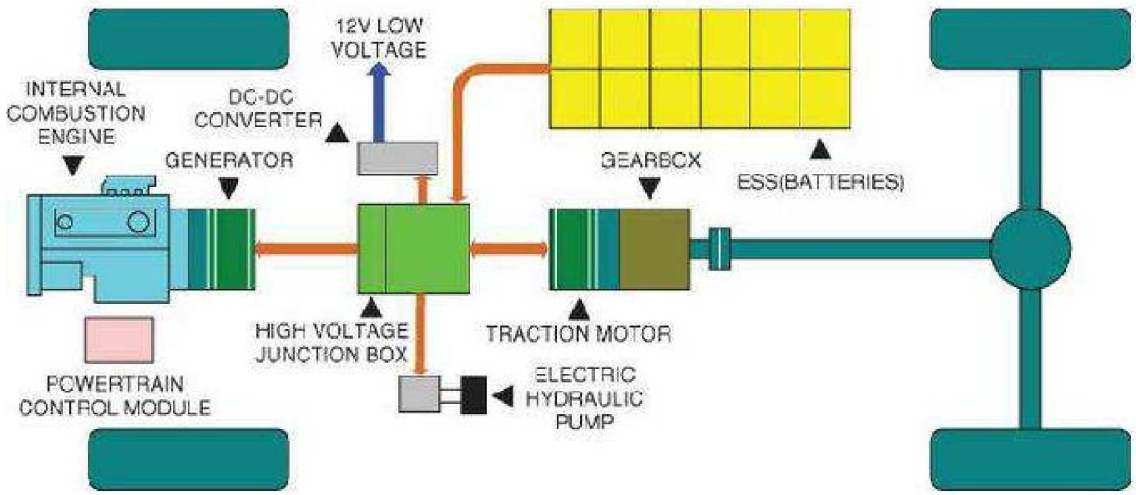

Figure 1 : *A Series Hybrid Electric Vehicle Layout (Rear-Wheel Drive) [Adapted from Liu]*

The main source of power is still liquid fuel, which is converted into mechanical energy by the ICE used to drive the generator. The generator converts this into electrical power and replenishes the energy storage system (ESS). The traction motor uses this electrical power to turn the wheels. Liu[2] remarks that a series hybrid is essentially an electric vehicle (EV) with an ICE acting as a 'genset' supplying electrical energy when the battery lacks energy to power the vehicle.

The state-of-art production version of this architecture is the General Motors' 'Voltec' powertrain that powers the Chevrolet Volt. The downsized engine is a 1398cc Straight-4 (EcoFLEX LUU) producing 62 kW that powers a 55 kW generator (also secondary motor)[3]. The primary traction motor can produce a peak 111kW[4]. The generated electrical energy mostly powers the primary motor, and charges the battery pack when there is a surplus during the low demand points of the drive-cycle. Hybridization Ratio of the GM Volt is 64 %, which puts it in the 'Plug-In Hybrid Electric Vehicle' (PHEV) Category.

In keeping with its classification based on the Hybridization Ratio, the Volt also has a 'Plug-In' functionality for charging up the batteries, without using the ICE. It can therefore be used in its most efficient 'All Electric' mode till the 16 kWh Li-ion battery pack runs out (40-80 km range). The range and performance (peak 111kW) in this mode, make this an ideal city car.

The main attraction of 'series' hybrid exists due to the fact that there is a significant efficiency increase achieved when ICE runs at near-constant demand at its peak efficiency point throughout the drive cycle.

1.2 Parallel Hybrid

The Parallel architecture differs from Series insomuch that both, the ICE and the electric motor are connected to the drive wheels through transmission and clutch[5]. Both the systems are capable of powering the vehicle either independently or in combined mode[1].

One advantage over Series architecture is that, Parallel hybrids only need two propulsion components, the ICE and the motor as opposed to three components in Series due to one motor and one generator. Another advantage is that at demanding parts of the drive-cycle, the load can be distributed between the ICE and motor, while in Series architecture the motor has to be powerful enough to deliver the peak demands. This allows for motors in Parallel architecture to be much smaller than those needed for Series, making packaging easier and eliminating motor operation in parts of the torque curve where the

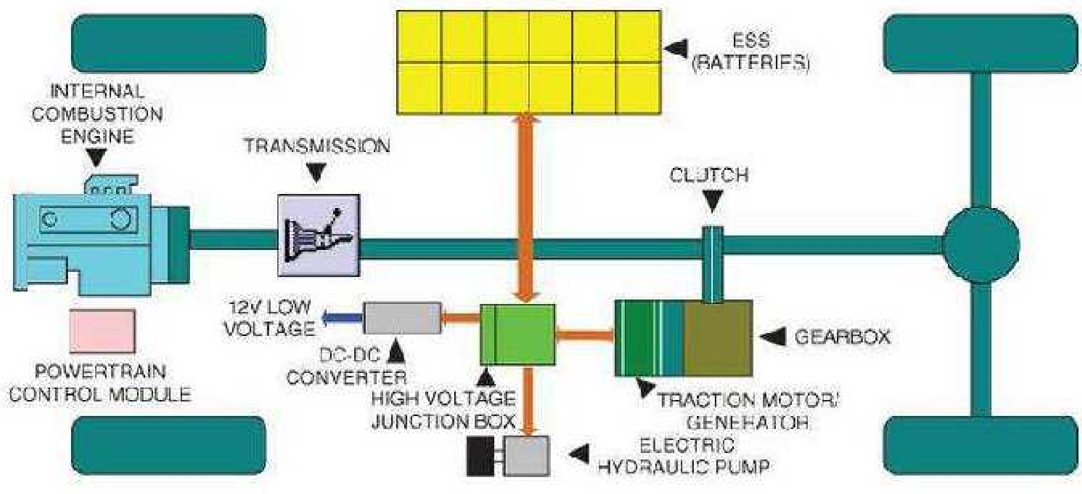

Figure 2 : *A Parallel Hybrid Electric Vehicle Layout (Rear-Wheel Drive) [Adapted from Liu]*

motor loses efficiency (eg. Above 70 mph, corresponding to a motor speed of 6500 rpm in a Series Hybrid - Volt, the primary traction motor begins to spin too rapidly and looses efficiency[3]).

The Honda Civic Hybrid has a parallel architecture, in which a 14.6 kW Permanent Magnet Synchronous Motor (PMSM) assists the 70kW ICE[6]. Examples of parallel hybrids also include the Porsche Cayenne S Hybrid and the Porsche Panamera S E-Hybrid (PHEV)[7].

1.3 Series-and-Parallel Hybrid

This architecture aims to capitalise on advantages on both of the previous architectures. The ICE is able to supply tractive power to the wheels, independently as well as along with the motor. It adds a generator

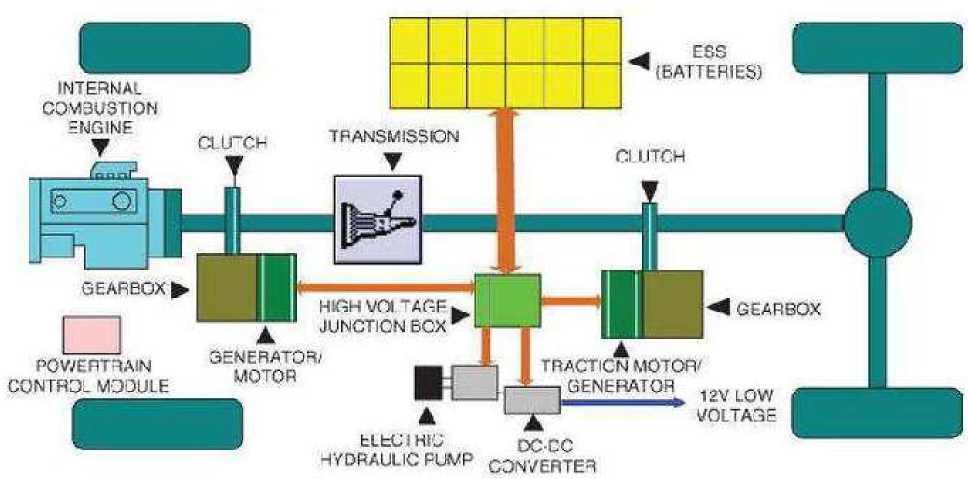

Figure 3 : *A Series-and-Parallel Hybrid Electric Vehicle Layout (Rear-Wheel Drive) [Adapted from Liu]*

to the ‘parallel’ architecture giving it the functionality to charge the batteries too, thereby reaping benefits of ‘series’ architecture.

The Toyota Prius, the world’s best-selling hybrid[8], now in its third generation is a variant of the Series-and-Parallel architecture. It uses a 1798cc Atkinson cycle, Straight-4 ICE capable of producing 73 kW[9]. The electric motor the Prius uses, while capable of producing 60 kW, is capped at 27 kW due to the battery power rating thereby bringing the combined power output of the Prius to 100 kW[9]. There are four driving modes available, which are a combination of its ability to run purely on electric, purely on ICE or using both at the same time. EPA estimated combined mileage of the Gen3 Prius is 50 mpg[8] and is also certified as an Super Ultra Low Emission Vehicle (SULEV). ‘Potential’ Hybridization Ratio of the Prius is 45%, however owing to the battery power rating limit, the actual Hybridization Ratio is 27%.

2. Components of ahybrid powertrain

While the internal combustion engine (ICE) has been evolving to better suit the automobile for well over a century, the other components that go into making a ICE-Electric hybrid vehicle have only a little more than a decade. Technology for these is in constant flux with frequentstep-changes. The following provides an overview of the state-of-art technologies currently existent for the various components of a hybrid drivetrain.

2.1 Electric Machine (Electric Motor/Generator)

The electric machine is the foremost component of the hybrid powertrain. There are various technologies that the electric machine can utilize and the choice strongly depends on the application. This implies that for different architectures, motors of different sizes and potentially different construction may be more suitable. A brief discussion about currently available motor technologies is followed by highlighting the type most suited to hybrids.

The three main options for automobile electric machines are – AC Induction motors, Brushless DC motors and Permanent Magnet Synchronous motors (PMSM).

TABLE 2 *A Comparison between various kinds of electric motors available for hybrid vehicles[Adapted from Cole]*

Feature	Induction	BLDC	PMSM
Mass	Medium power & torque density	Good power & torque density	Good power & torque density
Rotor inertia	Medium	Low	Low
Dynamic response	Adequate	High	High
Cost	Low	High (magnet)	High (magnet)
Efficiency	Low peak but better part load	High peak	High peak
Speed	Good range but speed control more difficult	Good range but SPM limited	AS BLDC but flux weakening possible
Other	Lower maximum torque range		Accurate sensor

AC Induction Motors and the *Brushless DC (BLDC) motors* are very similar in construction;there is no noticeable difference in their stators, howeverthe rotors vary. Induction motors have a few advantages over BLDC. They are cheaper to produce, since they do not needpermanent magnets. Safety circuitry is simpler and also cheaper since induction motors produce minimal back voltage while powering off. However, they have drawbacks such as lower peak efficiency due to their best power factor being about 85% [10] compared to near unity for BLDC motors.

Even so, as motors are scaled up, induction motors tend to become more efficient in comparison to BLDCs part loads since losses in permanent magnets (BLDCs) increase with scaling. This is why full EVs such as General Motors EV-1 and Tesla Roadster use induction motors instead. But, since hybrid vehicles have relatively small motors, these losses in BLDCs do not compromise the machine's efficiency. Induction motors also tend to produce more heat. Both, peak efficiency and heat levels being crucial factors for hybrids make BLDC motors much better suited for the application. This is the reason why brushless DC motors currently dominate the hybrid[10] and plug-in hybrid market.

The other permanent magnet (PM) electric machine that is a strong contender is the AC *Permanent Magnet Synchronous Motor* (PMSM). These machines do away with the knownproblem of 'cogging torque' produced by BLDCs at low speeds. This is important, since a lot of the hybrids (particularly ones with low Hybridization Ratios) run motors when at low speeds. PMSMs also have the potential for 'field-weakening', which allows them to run efficiently at higher than rated speeds, thereby overcoming another known problem of small constant power speed regions (CPSR) with electric motors.

Many Formula Student teams use gearing ratios on PMSMs for high torque and use field weakening

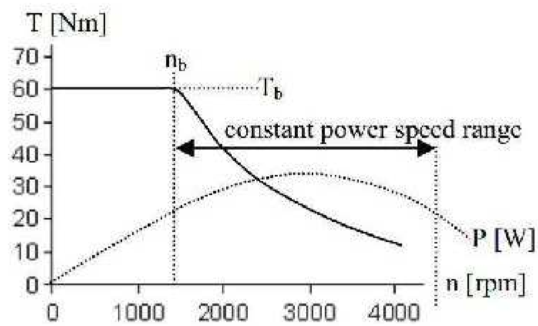

Figure 4 : *Torque versus speed characteristic of a PMSM motor demonstrating the Constant Power SpeedRange (CPSR) [Adapted from Conner]*

to extend the speed range of the vehicle. This is done by operating the motor in a closed feedback loop using an encoder or position sensor. While control algorithms for PMSMsare more complex, they exhibit lesser noise than BLDCs and much smaller torque ripples due toa less varying air-gap between the rotor and stator[11]. These are important considerations for driver comfort, since lesser noise and unwanted torque variation means a more comfortable ride. PMSMs can also potentially be more compact than BLDCs.

Owing to recent advancements in motor control development platforms, programming of the more complex sine waves (for PMSMs) versus the relatively simple trapezoidal controls (for BLDCs) can now be done without incurring exceptionally high development costs and expensive processors for the motor controller. These factors put together contribute to the fast rising popularity of these machines for applications in ICE-Electric hybrids, with the Gen 3 Toyota Prius[9] and Honda Civic hybrid[6] among others already using these motors.

2.2 Energy Storage Systems (ESS)

The ESS usually consists of batteries. Similar to the case of the motor, it is the application and demand that determines the type of chemistry, type of cells and the configuration they are used in. This application is primarily dependent on the type of hybrid electric vehicle (HEV), a good indication of which is the vehicle's position on the Micro-to-Full Hybrid spectrum. This can often to given by the Hybridization Ratio of the vehicles. In some cases, especially performance vehicles with 'full electric' driving modes, despite low hybridization ratios the power demand from the batteries to the motor can be high due to the large motor. Example, the Porsche Cayenne S Hybrid with a hybridization ratio of 12% (which puts it in the 'mild hybrid' class) is actually a full hybrid[7], capable of running 'electric only' mode on its 33 kW motor. The motor size belong to the 'full hybrid' class implying a high power demand (and consequently operating voltage) from the ESS.

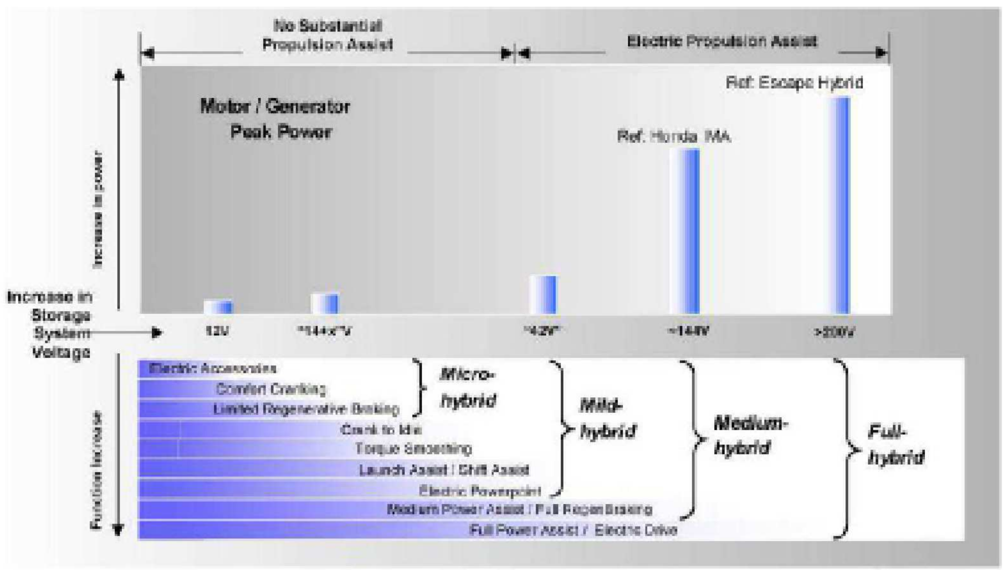

Figure 5 : Hybrid Classification based on incremental powertrain functionality [Adapted from Barcaro (12)]

Chemistry of Cells

Depending on the power and capacity requirements, cells of following chemistries are currently available

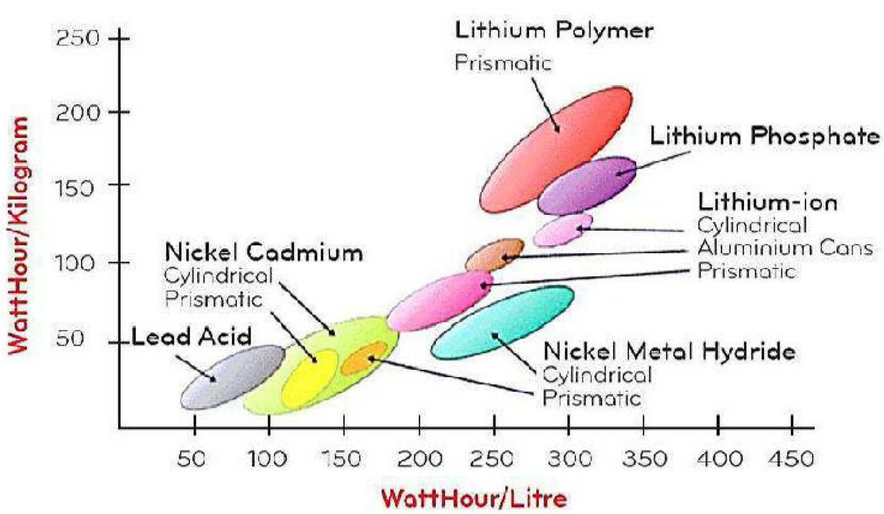

Figure 6 : Specific Energy and Energy Density for various battery chemistries [Image courtesy : Lite Plus Battery]

for hybrid vehicle applications. Other important considerations are the safety of the cells, reliability and cost.

Battery technology has developed by leaps and bounds over the past few years. Traditionally, Lead-Acid, used to be the dominant the chemistry of available batteries. However, despite being cheap and reliable, factors such as low specific power, poor energy density and short life-cycles[13] have confined these batteries to supporting ancillaries in HEVs and PHEVs today.

T A B L E 3 *Battery Specifications for Generations 1-4 of the Toyota Prius [Image courtesy : Toyota Motor Corp.]*

	97 Prius (Generation I) Japan Only	00 Prius (Generation II)	04 Prius (Generation III)	2010 Prius (Generation IV)
Form Factor	Cylindrical	Prismatic	Prismatic	Prismatic
Cells (Modules)	240 (40)	228 (38)	168 (28)	168 (28)
Nominal Voltage	288.0 V	273.6 V	201.6 V	201.6 V
Nominal Capacity	6.0Ah	6.5Ah	6.5Ah	6.5Ah
Specific Power	800 W/kg	1000 W/kg	1300 W/kg	1310 W/kg
Specific Energy	40 Wh/kg	46 Wh/kg	46 Wh/kg	44 Wh/kg
Module Weight	1090g	1050g	1045g	1040g
Module Dimensions	35(oc)x384(L)	19.6x106x275	19.6x106x285	19.6x106x285

The most widely used batteries in ICE-Electric hybrids are Nickel Metal Hydride (NiMH) and Lithium-ion (Li-ion). Vehicles such as the Toyota Prius, Honda Civic Hybrid, Citroën C4 hybrid HDi use NiMH batteries while the GM Volt uses Li-ion.

Currently 95% of all HEVs use NiMH batteries[14]. The reason for recent increasing interest in Li-ion batteries, has been due to the shortcomings of their NiMH counterparts such as high self-discharge, high costs and heat generation at high temperatures[13]. Li-Ion batteries also have better specific power and energy densities *(see table 3).*

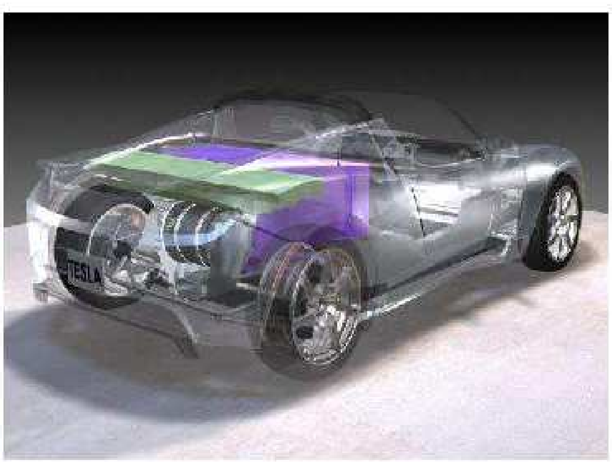

Figure 7 : Location of Battery and BMS on TeslaRoadster [Image courtesy : Tesla Motors]

This is most crucial for EVs, due to higher power and energy demands. Weight and volume become pressing issues very rapidly which is why most EVs such as the Tesla Roadster use Li-Ion batteries as opposed to NiMH. These concerns, while not as crucial for HEVs and PHEVs are still important and becoming even more so with introduction of high performance PHEVs.

Reuters[15] has reported that Toyota Motor Corp is also planning to increase production of lithium-ion batteries with the intent of using them on the future Prius models.

Type of Cells

The decision regarding types of cells – prismatic, cylindrical or pouch depends on an array of factors, primarily packaging constraints, costs and thermal management. For example, while prismatic cells are easier to package due to their compact nature, thermal management for them is more complex than for cylindrical cells.

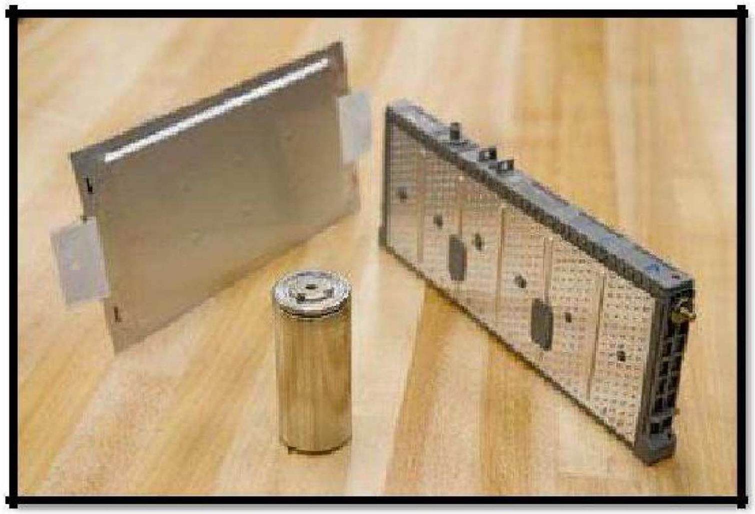

Figure 8 : *(Left to Right) Pouch cell, Cylindrical cell and Prismatic Cell]*

In production hybrids, pouch cells are rarely used due to the complexity of mechanical support they require. Thus, most hybrid vehicles use prismatic or cylindrical cells. Where large batteries are needed, such as in high hybridization-ratio PHEVs like the Toyota Prius (168 cells)[16] and the GM Volt (288 cells)[17], prismatic cells tend to be used. Mild Hybrids, such as the Honda Civic Hybrid, which need significantly lower battery capacities and power output, cylindrical cells can be used due to the absence of excessive packaging constraints.

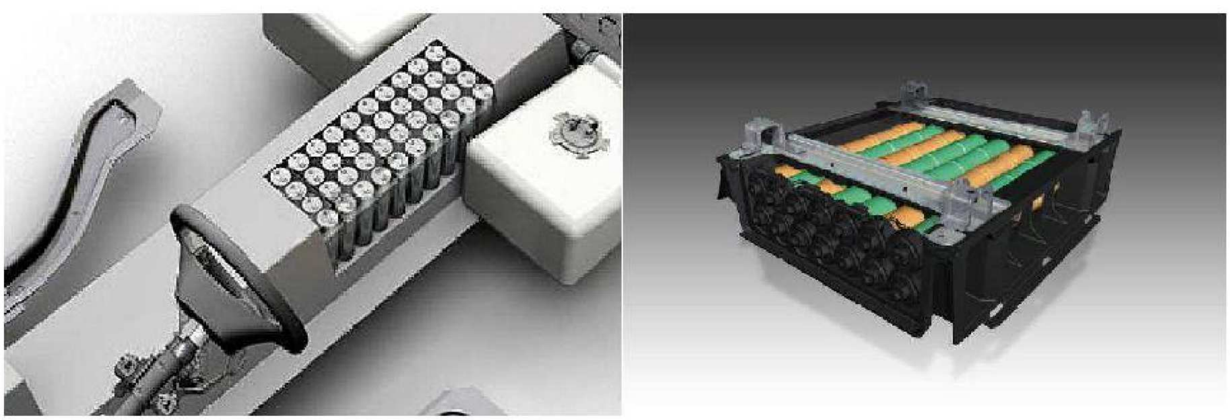

Figure 9 : *a) Rendering showing Cylindrical Cells b) Cylindrical cells in a battery pack for Honda Civic Hybrid*

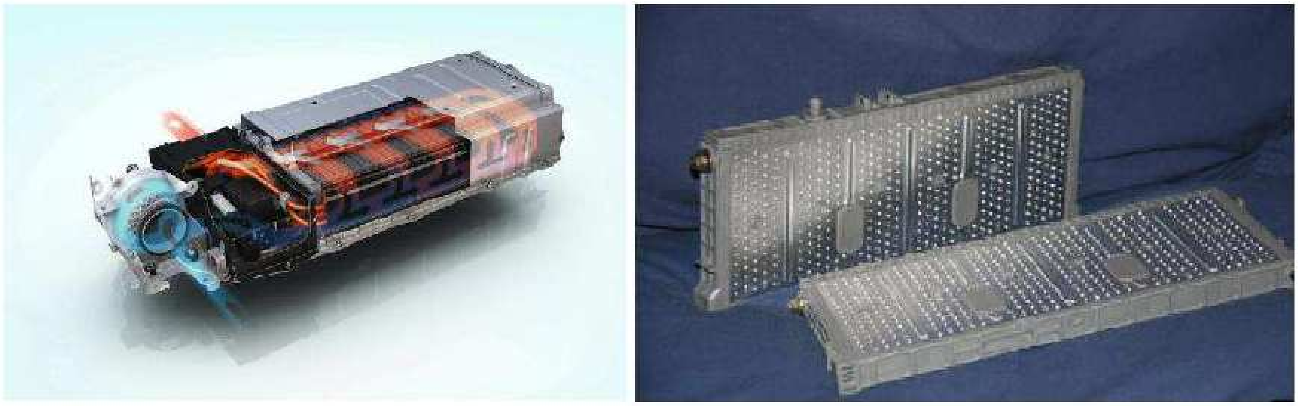

***Figure 10** : a) Illustration of Prius Prismatic cell battery pack b) Prismatic cells of the Prius[Image Courtesy : cdn.carthrottle.com]*

Configuration of Cells/Modules

Once the chemistry and type of cells have been fixed, the Series/Parallel configuration depends on the voltage required for the High Voltage (HV) system and the capacity required (kWh). Stacking cells or modules in series increases both, the voltage and the capacity of the pack. However, if only the capacity needs to be increased, without increasing the voltage, then ‘parallel’ configuration is used. For example, 24S-2P configuration means there are 24 cells connected in series, and two such packs connected to each other in parallel.

2.3 Battery Management System (BMS)

Battery packs used in HEVs and PHEVs are often made of up hundreds of cells connected in a mix of series and parallel configurations. The purpose of the BMS is to ensure that all cells are functioning the way they are supposed to and to provide safety features such as warnings to the user or in extreme scenarios, cutting power to the HV tractive system.

Heat generation in batteries is a major concern and threat to safety and reliability of hybrid and electric powertrains. This necessitates measuring of temperature of a percentage of cells for indication of state, and for the more ‘volatile’ chemistries even that of every individual cell. This is done by the BMS. Other important parameters of batteries that need to be monitored are :

State of Charge (SoC) : It is a reflection of the battery capacity in terms of percentage,aimed at depicting the amount of remaining battery life. The SoC cannot be measured directly and the BMS usually uses one of the following ways to measure it – Coloumb Counting, Specific Gravity Measruements or Kalman Filter estimation method[18]. Batteries in HEVs are usually kept at 50% SoC and not allowed to go above 75% or below 30% [19]. For PHEVs the SoC is kept between 100% (when charged overnight) down to 10% [19].

State of health (SoH) : It a reflection of the overall condition of the battery.

Voltage : Total voltage of the pack, voltages of individual cells, minimum and maximumcell voltage. (Prius BMS measures voltage of every second module[20])

Depth of Discharge (DoD) : It is simply the complement of SoC and is used tocharacterize the load-cycle the battery experiences.

The BMS may be ‘Active’ or ‘Passive’.

Passive : A passive BMS only monitors the various battery parameters andcommunicates them to the Vehicle Control Unit (VCU) for display of data logging. This is usually done via CAN or serial communication (such as RS-232 or RS-485).

Active : An active BMS on the other hand, has the capability to alter the state of thebatteries. It has the functionality to be fed ‘trigger events’ using control algorithms, such as cutting-out a particular module if its temperature becomes too high or voltage drops below a certain point. It also has the capability to perform ‘cell balancing’, which isessentially charging or discharging individual cells to bring them at uniform voltages for better battery performance.

Most production HEVs and especially PHEVs, including the Porsche Cayenne S Hybrid, Honda Civic Hybrid, Toyota Prius, Fisker Karma use highly sophisticated ‘Active BMS’s due to high reliability and low maintenance expectations from users.

2.4 Power Electronics and Controls

Power Electronics perform the crucial, and often under-rated task of the integrating the various components of an ICE-Electric hybrid drivetrain.

Inverter/Motor Controller

The most important component of the power electronics of a hybrid vehicle is the inverter/motor controller.

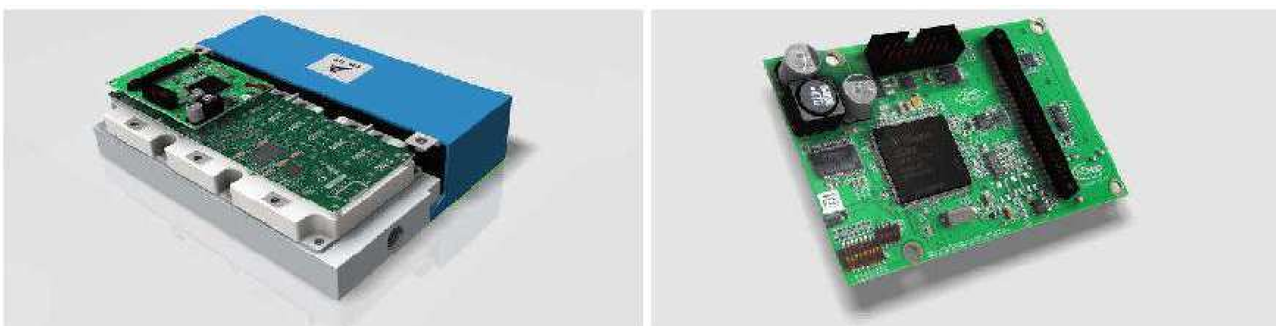

Figure 11 : *a) CAD rendering of the Infineon HybridPack 2 Inverter/Motor Controller by Warwick RacingElectric and b) Logic board responsible for controls and Pulse-Width Modulation (PWM)*

Since ESS of the vast majority of hybrid vehicles produce DC power and the best motors for powering the wheels tend to be AC *(see section 2.1)*, the main task of the inverter is to convert this DC power from the batteries to AC.

Like with other components, the inverter rating (sizing) depends on the Voltage and Power requirements of the vehicle as dictated by the level of hybridization. Typical inverters for production ‘full hybrid’ vehicles are rated at 650V, ranging from 300V to 800V. A typical peakcurrent rating is 800A, but they are capable of functioning with much lower currents. The Toyota Prius has a system voltage rating of 650V, despite the nominal rating of the battery being just a little over 200V (21).

IGBTs : The main part of the conversion from DC to AC is performed by 3-pairs of IGBTs‘switching’ at a phase difference of 120 degrees in order to generate the three sine-waves (or current) required to rotate the magnetic field inside a motor, thereby generating the required torque and speed.

Capacitor (blue box in figure 11 a) : The Capacitor is vital for safe and smooth workingof the motor. It is present to reduce the noise generated in the ‘AC current’ to the motor. This is especially important at high rotational speeds of the motor, when the waveforms have increasingly poorer resolutions resulting in greater levels of noise.

Printed Circuit Boards (PCBs) : Typically, one PCB is the*'Driver Board'*while the otheris the *'Logic Board'*. While the driver board contains the wiring to enable the control signals to switch the IGBTs as required, it is the logic board that has the processor and contains the control algorithms which perform Pulse Width Modulation (PWM) to produce waveforms with the required frequency (controls motor speed) and amplitude (controls motor torque). The logic board also contains the connectors for CAN and Serial (usually RS-232) communication for development purposes.

The Infineon HybridPack 2 is primarily a development kit, however there are many production inverters/motor controllers available that are based on its architecture. For example, the EV Westfield iRacer uses a Sevcon-Gen4 Inverter *(pictured below)* that is based on the Infineon HybridPack 2, with the additional safety circuitry and mechanical durability to perform well in harsh conditions (compared to a laboratory) that hybrid vehicles may be put through during their life-cycle.

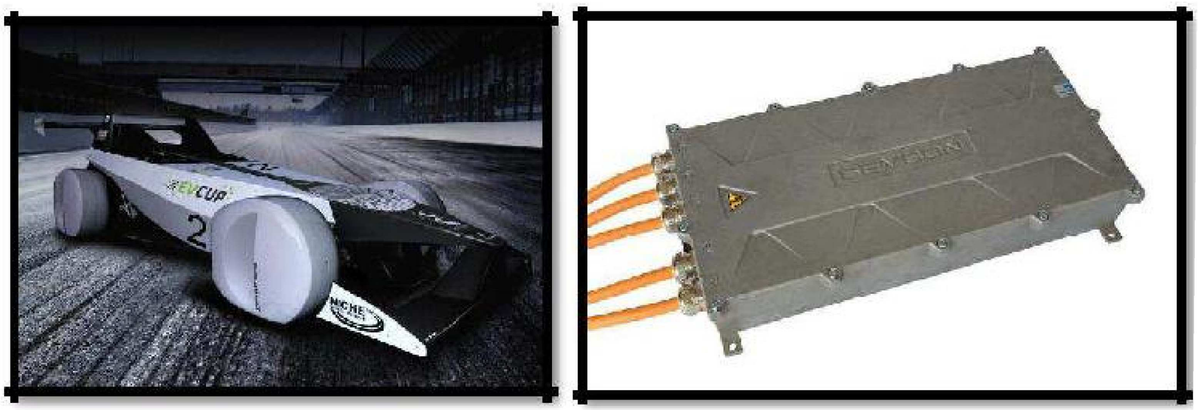

Figure 12 : *a) Westfield iRacer* *b) Sevcon Gen4 Size 10 inverter [Image courtesy : Sevcon]*

DC-DC Converter

In HEVs and especially PHEVs, since the ICE may not be powered on for prolonged periods, like the vehicle constantly being used in its EV-only mode the low-voltage (LV) battery may not get recharged through an alternator.

Figure 13 : Toyota Prius DC-DC Converter [Image courtesy : Toyota Motor Corp]

This is the reason why, most hybrids on sale today have a DC-DC converter which steps down the HV battery's voltage down to 12V of the LV battery to top it up. The Toyota Prius also uses a DC-DC converter[22] to step down from its 201.2V HV System to the 12V LV battery that supports the ancillaries.

Current Challenges for Hybrid Vehicles

While ICE-Electric Hybrid vehicle technology has been highly dynamic and fast evolving over the past decade, there are various challenges that are yet to be overcome fully. These can be readily split into – technical, economic and social challenges.

1.Technicalchallenges

1.1 Batteries; Batteries, arguably are the weakest link in the chain for hybrid vehicles at present for a number of reasons :

Low Energy Density : The energy density of liquid hydrocarbons (such as gasoline) isaround 12,000 Wh/Kg [23], while that of the Lithium-Ion batteries is about 120 Wh/Kg [24]. This implies that a tank of gasoline contains almost 100 times the energy of an equal mass of batteries. Low capacity, implies low range which is one of the biggest barriers to consumer acceptance of HEVs and PHEVs.

Long Charging Times : While filling up at the gas station, barely takes a few minutes,currently the charging times for PHEVs range anywhere from 4-12 hours. In order to overcome this, the batteries would need to be developed that can take high rates of charging (measured in terms of 'C' value) at affordable prices and charging stations capable of delivering high power. This involves finding a solution to providing high power charging in households. Presently, the average power load of a household is considered to be 2 kW[24] and the utility supply is not capable of delivering much more therefore charge rate of the Chevrolet Volt is limited to 3.3 kW[24] resulting in the long charging times. Infrastructure for 'Level II' and 'Level III' charging stations needs to be developed and made accessible to reduce these times.

T A B L E 4 *Charging Power Levels*

Charging level	Typical charging power
Level I	1.5–3 kW
Level II	10–20 kW
Level III	40 kW and up

High Variability : Metal-hydride and Lithium-ion batteries are highly sensitive totemperature changes due to the fundamental fact that chemical reactions occurring inside them require optimum temperatures to function. This makes them highly vulnerable even to common day weather changes, like humidity and temperature.

Thermal Management : If the battery temperatures drop too low, they rapidlydischarge even when they are not producing any power. In order to keep the batteries in the optimum temperature ranges, they often need to be pre-heated when staring on a cold day and cooled after a certain amount of time. This makes the thermal management and its control a highly complex and expensive undertaking.

*Poor Characterization :*In order to be able to design and predict the performancecharacteristics of a HEV or PHEV before production, a simulation model of the batteries needs to be created. However, understanding of battery chemistry is still not exhaustive enough to be able to make virtual models capable of correctly simulating the behaviour of the batteries for different load-cycles and varying conditions. Even state-of-art batteries are developed using methods heavily reliant on testing and trial-and-error, resulting in extravagant development costs and still fair amount of unpredictability.

1.2 Power Electronics; While DC-DC converters are comparatively 'passive' devices, the DC-AC inverter/motor controller has very high performance requirements and this creates a few design challenges :

Switching Frequency : As briefly stated earlier*(see section 2.4 : Power Electronics)*,theIGBT pairs in the inverter have to switch on and off many times a second in order to create smooth sinusoidal waveforms. This is the switching frequency (or PWM chop frequency) and is state-of-art inverters have IGBTs typically capable of 10 kHz for production hybrids. For example, the Prius inverter has two switching modes of 5 kHz and 10 kHz [25].

This is a problem if hybridization is to expand to performance cars where high vehicle speeds are an accepted customer expectation, since the IGBTs may not be able to switch fast enough resulting in drastic loss of performance or the system shutting down.

Heat Generation : Since all the power that the motor outputs has to go through theinverter, a lot of heat is generated due to inefficiencies. These inefficiencies need to be minimized in order to remove the need for complex cooling systems.

1.3 Controls and Regenerative Braking; Since electronic and electrical response is near-instantaneous, the acceleration and braking behaviour of the HEVs, especially series hybrids can seem 'non-intuitive' and even jerky at times. Since the consumer has been accustomed to the mechanical inertia and friction of the engine slowing down the vehicle at times of throttle 'lift-off', the instantaneous loss of power and significantly lower friction of the motor may have implications for driver comfort.

This problem is accentuated in the case of regenerative braking where lifting off the pedal causes active braking due to the negative torque being produced in the motor. The amount of braking that occurs also varies depending on the SoC of the battery at the time, since at different levels of SoC the battery behaves differently and will take back different levels of power, causing the braking to be unpredictable to an extent. This is a common driver complaint[26], especially in series architectures or while running in the EV-only mode for others. Solving the issue effectively, entails controls and calibration challenges that need to be overcome.

2. Economic challenges

The upfront costs of purchasing a HEV or PHEV are significantly higher than the conventional ICE counterparts. This is a big deterrent towards consumer acceptance of hybrids. The high prices of these vehicles are rooted in the following factors.

2.1 High battery manufacturing costs; High manufacturing costs of batteries currently is one of the key reasons why HEVs, and especially PHEVs are expensive.

While current prices are around $1500/kWh, future estimations predict the prices reaching the $250/ kWh mark. This shift will greatly help manufacturers produce hybrids that are almost competitive in price to the conventional counterparts.

For example, the NiMH battery pack for the Prius costs around $3000 currently[14] but with cost around $600.

T A B L E 5 *Battery Prices [Adapted from Cole]price decrease, would only*

Who[40]	Price ($/kWh)	When	Comment
Recent price data			
EUROBAT (2005)	1,000-2,200	2005	€700-€1,500 (at €1=$1.48)
Challenge Bibendum Battery Round Table (2007)	1,000-2,000	2007	
Future price projections			
EUROBAT (2005)	296	2020	€200/kWh (at €1=$1.48) target at end of 15 year research programme; 100k production volume/annum; 30kWh battery
ANL (2000)	250	Future	Optimistic projection based on future price of materials
IEA (2005)	270	Future	Data taken from EPRI 2003. Plus $800 balance of plant
EPRI (2005)	280	Future	100k production volume/annum; 30kWh battery
CARB (2007)	240-280	Future	100k production volume/annum; 25kWh battery
Long-term target			
USABC	100	Long-term target	25k production volume/annum; 40kWh battery

In the meantime, governments in various countries are offering discounts and incentives in various forms to encourage people to shift to EVs and HEVs. For example, the US Government gives an incentive of $8000 for the Nissan Leaf (EV) and similar incentives exist for HEVs.

2.2 High cost of permanent magnet (PM) electric machines; As discussed earlier *(see section '2.1: Electric Machine')*, PM machines like the BLDC motor and PMSMs are best suited for hybrid vehicle application. The problem with PM machines is that they tend to use rare earth metals such as Neodymium and Dysprosium. The following graph shows their price per unit mass.

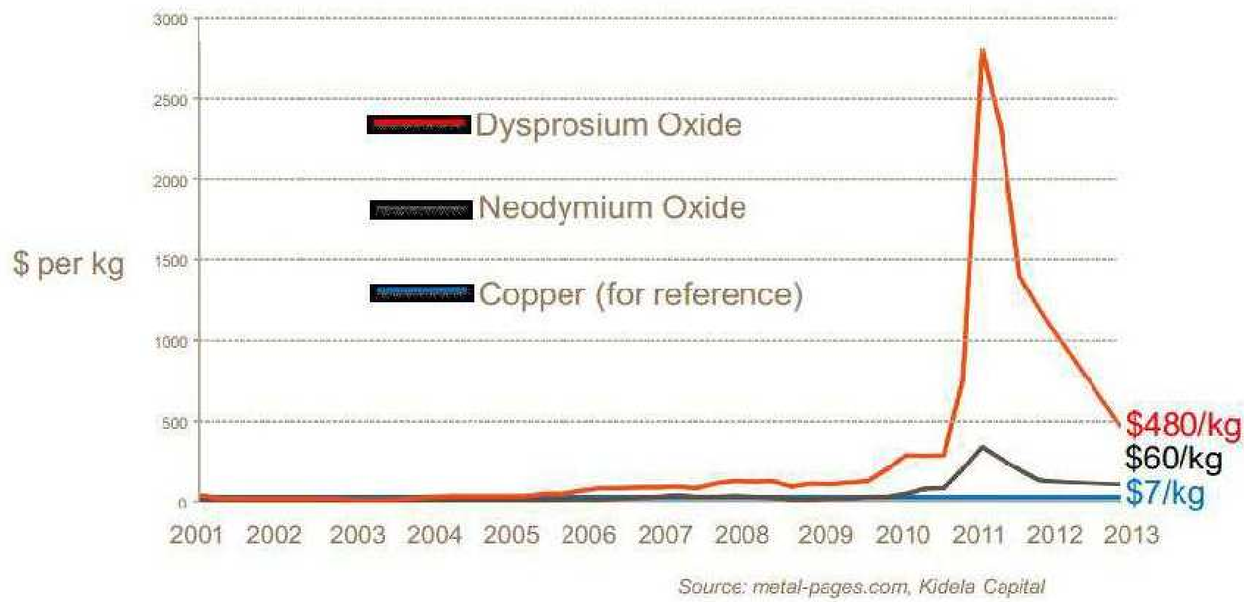

Figure 14 : *Prices ($) of RRE versus time*

Reducing the use of rare earth metals in hybrid vehicles will reduce their production costs. According to Rare Earth Metals Inc.[27], the Toyota Prius contains about 30 Kg of rare earth metals. Diagram below shows where in the car these rare earth elements (REEs) are distributed and therefore potential areas for reduction.

Figure 15 : *Distribution of RRE in a Prius*

[Image Courtesy : allaboutprius.com]

Future Technologies

Since the ICE-Electric hybrid vehicle is a relatively new market, there is constant innovation due to extensive research & development by established OEMs as well as specialized companies and start-ups. A few upcoming technologies are discussed below.

1. Hubmounted motors

The idea was, surprisingly enough pioneered by Dr. Ferdinand Porsche before turn of the 20^{th} century, in 1898. First prototypes were battery powered EVs with two front wheel hub-mounted motors. He built upon that, and developed a 'series-hybrid' with hub-mounted motors in each wheel. A general schematic of a series HEV with hub mounted motors is shown below.

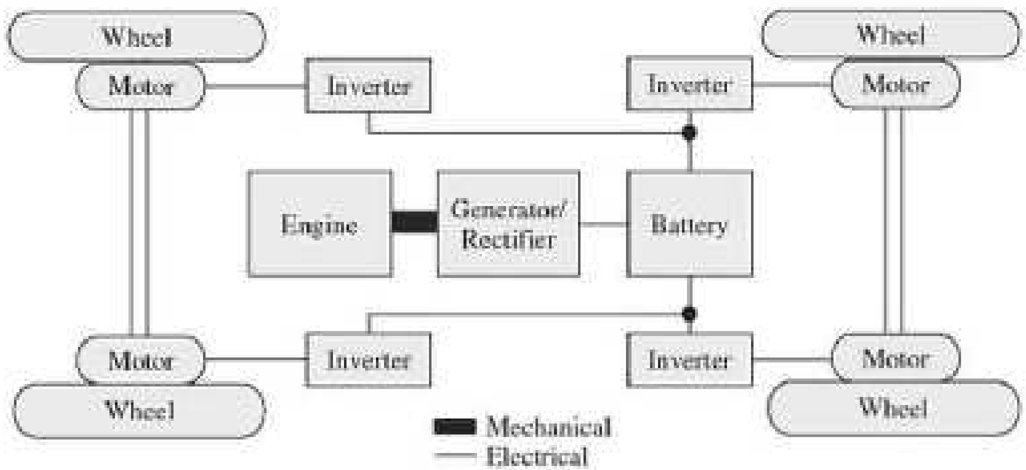

Figure 16 : Hub motor configuration of a series HEV [Adapted from Gao]

The main advantage of this configuration is that it removes the need for a large tractive motor, driveshaft, differential and half-shafts[28], creating a lot of space in the 'bulk' of the vehicle which can then be used for various other purposes. There are multiple names for the concept such as 'hub motors', 'wheel mounted motors', 'In-Wheel motors'.

From a technical design perspective, since the application requires the outside of the motor to be spinning, not all motors are suitable. However the current developments are based aroundthe Surface mounted Permanent Magnet (SPM) motor, as its topology is suitable for an External Rotor machine[6]. Protean Electric's 'In-Wheel' *(pictured below)* design uses this type of motor; they have recently converted a Brabus Mercedes-Benz E-Class into a plug-in hybrid and have integrated their In-Wheel motors in the two rear wheels. This design allows electric drive to be added to stockwheels and without altering the drivetrain of the vehicle[29].

Various other prototypes have also been developed, based on the same concept but with slightly different designs, such as Michelin's ActiveWheel *(pictured below)*. This design minimizes the problem of large unsprung massed due to the smaller motor being used as compared to Protean's In-Wheel motor.

Figure 17 : *a) Brabus Mercedez Benz E-Class converter by Protean b) Protean's In-Wheel motorHub [Image Courtsey : Protean Electric]*

The concept of wheel mounted motors offers promising potential, with its modular approach to implementing electric drive.

Figure 18 : *Michelin's ActriveWheel Motor*

[Image Courtesy : coroflot.com]

2. Innovative charging

Various technologies are being developed to make charging of hybrid vehicles easier, more practical and accessible.

2.1 Wireless Charging for 'Plug-less Hybrids'; Most notable efforts include wireless charging. Nissan's efforts utilize Electromagnetic Induction and achieve charging efficiencies of 80-90%[30], which is equivalent to charging via cable. Similar systems have been developed by Evtran in collaboration with Bosch, and also by Toyota.

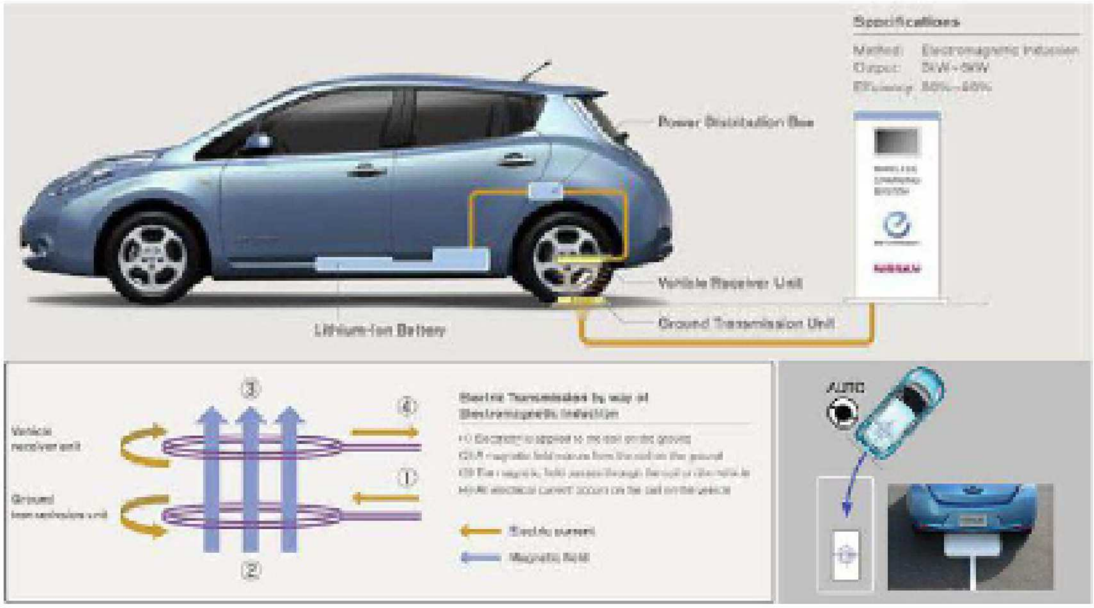

Figure 19 : Nissan's Electromagnetic Induction Charging [Image Courtesy : Nissan Motors]

2.2 Solar Charging; Another technology that is being pursued by the industry for charging batteries is to use innovative ways to harness solar power since the surface area of the vehicles is limited.

Ford's C-MAX Solar Energi Concept, uses special concentrator lenses on its roof to focus the rays of the sun, while acting as a huge magnifying lens. It further maximises its charging potential using the built in 'autonomous repositioning' feature[31] to best position itself with the movement of the sun. The technology is capable of fully charging the vehicle's 8 kWh battery in only 8 hours while standing in the sun. Even charging from a dedicated power source via cable, would take no less than 4 hours in comparison.

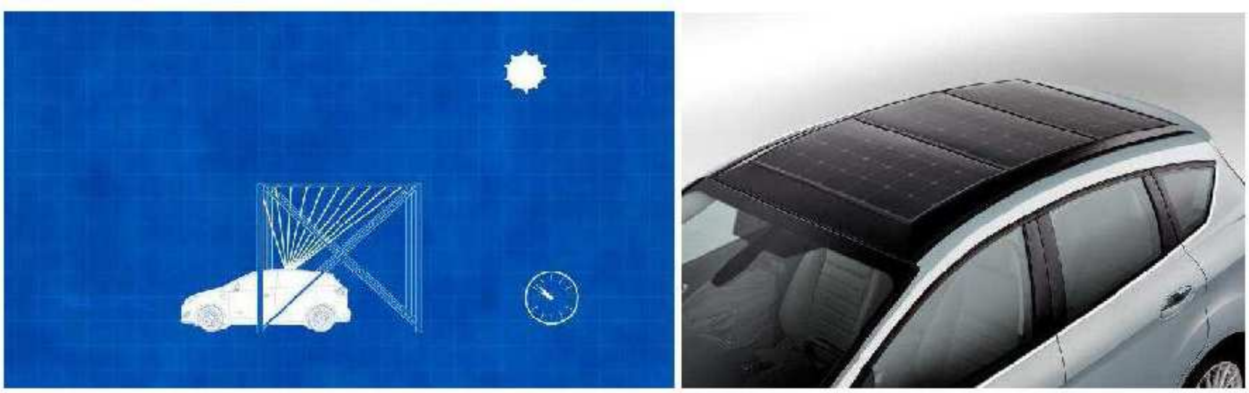

***Figure 20 :** a) Showing working of Ford's C-Max concentrator lens b) Photo of roof of the Ford C-Max*

[Image Courtesy : SAE International]

Another technology that aims to capitalize on solar power is the 'PURE-Tension' fabric designed by SDA Design for Volvo. It is a flexible fabric supported by bending rods which forms a 'canopy-like' structure over the vehicle. The fabric is embedded with PV cells to harness solar energy.

Charging performance is as yet unconfirmed and is still in development.

3. Phasin goutraree arthmetals from motors

Permanent magnets have Rare Earth Elements (REE) that are expensive and have energy intensive extraction and refining processes, giving them a significant carbon footprint. Having established that PM electric motors are best suited for hybrids *(see section 2.1 : ElectricMachine)*, it is crucial to develop a technology that delivers the same performancecharacteristics are currently used PM motors without using REEs and the Switched Reluctance Motor (SRM) is being further developed for this purpose. It holds a future in hybrid vehicles as long as its main draw-back of high 'torque ripples' can be engineering for.

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