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# HISTORICAL TRENDS AND PARAMETER RELATIONSHIPS IN THE DESIGN OF ARMORED FIGHTING VEHICLES

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**ABSTRACT**

*The classic trinity of armored fighting vehicle design is the tradeoff between Armament, Armor, and Mobility. In a practical design, all three cannot be simultaneously maximized, so engineers must determine the proper balance between these capabilities, which would offer optimal combat performance, taking into account the limitations of industrial mass production. This study explores trends in the historical evolution of combat vehicles, from their initial appearance on the battlefields of World War 1 to the modern era. Additionally, this study also examines the basic physical limitations of combat vehicle design as a whole, by presenting fundamental performance limits that are universal to all classes of combat vehicles. This analysis is used to identify key areas of research that would be of significant benefit to the development of future combat vehicles.*

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## 1. INTRODUCTION

The classic armored fighting vehicle (AFV) design trinity is the tradeoff between Armament, Armor, and Mobility [1]. In a practical design, all three cannot be simultaneously maximized to their greatest available potential, so military planners must decide what balance of these capabilities would result in the best battlefield performance for their combat vehicles. Over the past century of AFV development, this balance has evolved and diversified, to comply with the increased number of operational roles performed by different classes of AFVs on the modern battlefield, a growing variety of new threats, the appearance of novel technologies becoming readily available to military engineers and manufacturers, and the need for efficient and sustainable mass production [2]. This study explores trends in the historical evolution of AFVs, from their initial appearance on the battlefields of World War 1 to the present day, as well as basic physical limitations of present day AFV design. The study further examines how these trends and limitations play a role in the design of future AFVs.



Arguably the most important element of the AFV design trinity is the mobility of the vehicle: a combat vehicle with a large gun and thick armor that cannot actually drive anywhere is just a pillbox [3]. As the power output and power-to-weight ratio of engines continue to grow, they enable the development and production of larger, more capable AFVs, carrying increasingly powerful armament, able to engage a wide range of hostile targets, fulfilling multiple operational roles. In turn, simultaneous international improvement in primary armament and associated ammunition drives the development of heavier, more effective armor protection, to ensure the vehicle can survive attacks by hostile battlefield assets. The increased weight of required armor packages, as well as new gun systems, in turn drives the need for continued development of more powerful, weight-efficient engines. Thus, in effect, the entire design trinity evolves continuously, driven by advancing mobility capabilities.

In this study, we examine the history of AFV design. We begin with a brief historical overview of the major categories of armored fighting vehicles included in the study, so that the subsequent data can be properly contextualized with the intended purpose of each vehicle class. We then continue to present historical trends in combat vehicle size, mobility, firepower, and armor protection. Where practical, we use the available historical data to derive basic underlying relationships characteristic of the set of examined vehicles, and use said relationships to identify areas of potential technical improvement. Finally, in the summary concluding this study, we discuss several proposed areas of research that would be of significant benefit to the development of future armored fighting vehicles.

## 2. MAJOR VEHICLE TYPES EXAMINED

The most famous class of armored fighting vehicle is certainly the tank. Since their introduction at the Battle of Flers Courcelette in September 1916 [4], tanks have been an indispensable asset of land warfare, providing fire support to friendly infantry, demolishing enemy fortifications, disabling hostile tanks, and occasionally even providing long-range artillery bombardment. In the century that has passed since the Great War, however, the original concept of the tank has evolved into a variety of specialized combat vehicles, whose design is focused on performing specific combat missions well, since it is impractical to design vehicles capable of fulfilling all possible battlefield roles cost-effectively. The evolution of several of the most common combat vehicle categories is examined in this work.

### *2.1. Tanks*

Experience gained by the British and French armies, during the first few months of tank deployment on the Western Front in 1916 and 1917, helped determine and solidify the basic guidelines of tank design, first combined in the French Renault FT light tank, developed in 1917 under the leadership of Colonel Jean Baptiste Estienne [5]:

- A tank should drive on continuous treads, as they provide superior cross-country mobility
- A tank should have a fully traversable turret for its main gun, as part of a combat compartment positioned at the center of the vehicle
- A tank should have the driver's position situated at the front of the vehicle, so the driver is provided the best possible visibility
- A tank should have the engine compartment isolated from the crew, in the rear of the vehicle

This classic tank layout is demonstrated using the Japanese Type 95 light tank in Figure 1. After World War 1 ended in 1918, many developed nations began to experiment and diversify their tank designs, with a variety of new classes appearing during the Interwar Period, specialized for distinct operational roles. These included infantry fire support, destruction of enemy tanks, battlefield reconnaissance, high speed flanking of enemy positions, and breaching of heavily fortified defensive lines. By the beginning of World War 2, advanced doctrines were developed to take advantage of the capabilities offered by these new classes of tanks, such as the Russian doctrine of Deep Offensive Operations.

**Figure 1:** Type 95 Ha-Go Light Tank

By the 1930s, tanks were classified into light, medium, and heavy categories by most nations [6]. While the most numerous category throughout the 1930s was the light tank, medium tanks quickly became dominant during World War 2: many designs were developed as enlarged derivatives of successful light tanks of the Interwar Period. These new tanks were intended to be all-purpose combat vehicles, capable of performing most battlefield roles adequately while being economical enough to rapidly be produced in large numbers. Medium tanks such as the American M4 Sherman [7], shown in Figure 2, and the Russian T-34 [8], made up the bulk of their nations' armed forces during the Second World War, with tens of thousands produced and sent into combat by the United States, the Soviet Union, and Germany.

**Figure 2:** M4 Sherman Medium Tank

While medium tanks were the mainstay of armored forces throughout World War 2, lighter vehicles were still needed for screening, reconnaissance, and infantry support in terrain inaccessible to medium tanks, or in less intense sectors of the front [9]. Thus, light tanks retained an important supporting role throughout World War 2. Most light tanks were armed with a modest main gun, less than 50mm in caliber, though some were armed only with machine guns, as seen from the example of the T-26 M1931 [10], shown in Figure 3. Armor protection of light tanks was often only sufficient to stop heavy machine gun ammunition, thus they were not intended to directly engage in combat with the main enemy army. Notably, some light tanks developed late in World War 2, like the American M24 Chaffee [11], were armed with guns as large as 75mm in caliber, making them more capable than even some medium tanks of the early 1930s.


**Figure 3:** T-26 M1931 Light Tank

The third major weight category of traditional tanks were the heavy tanks. These were built and used in much smaller numbers than medium or light tanks, and were primarily intended to break through difficult enemy defenses during major assaults. To fulfill this role, heavy tanks were protected with the thickest armor that could be practically used, and armed with the most powerful, large-caliber, long-barrel tank guns [12]. The speed, maneuverability, and cross-country mobility of heavy tanks was typically inferior to their lighter counterparts, but this was considered an acceptable limitation, because their primary intended role was to demolish enemy fortifications and strongpoints and destroy entrenched enemy heavy tanks, while the accompanying medium tanks would engage the remainder of the enemy force once a breakthrough was achieved [13]. An example of a heavy tank is shown in Figure 4, the American T30, designed at the end of World War 2, though built too late to see action.

**Figure 4:** T30 Heavy Tank

Most nations during the Interwar Period, World War 2, and the early Cold War classified their tanks as light, medium, and heavy tanks. However, a separate system was in use in Britain, France, and to some extent, Russia, during the Interwar Period, though Britain was the only nation to keep this classification throughout World War 2. Under this system, light tanks remained as their own category, but medium and heavy tanks were instead classified into infantry tanks and cruiser (or cavalry) tanks. Infantry tanks, such as the A22 Churchill Infantry Tank Mk.4 [14] in Figure 5 were designed as successors of the original World War 1 British tanks, intended for the sole purpose of supporting the infantry in attack. As such, the vehicles were built with thick armor protection, but much lower top speed than any other contemporary tanks, generally under 25 km/hr. Infantry tanks spanned the medium and heavy weight category of the time, ranging from 20 tons to 40 tons, depending on the model. The armament of British tanks in general was subpar for most of World War 2, as compared to German, Russian, and American tanks of the same era, though it was gradually improved towards the last couple of years of the war.

**Figure 5:** A22 Churchill AVRE Infantry Tank

Cruiser tanks, on the other hand, were designed for high speed charges deep into enemy territory, once the main defensive lines were breached by the attack of infantry tanks and their supporting foot soldiers. British military strategists expected cruiser tank units to focus on disrupting enemy supply lines and attacking command posts, which would sever communication with the rear and prevent enemy forces from quickly responding with a counterattack, as envisioned by Major General J. F. C. Fuller in his Plan 1919 strategy [15]. Thus, the greatest focus of cruiser tank design was speed, so armor protection was reduced to an acceptable minimum. Armament of cruiser tanks was generally comparable to that carried by the slow infantry tanks, though it saw much more improvement by the end of the war, as cruiser tanks like the A34 Comet Cruiser Tank (Figure 6) began to be armed with the outstanding 17 pounder anti-tank gun, previously mounted on the Firefly modification of the US Army M4 Sherman tank.


**Figure 6:** A34 Comet Cruiser Tank

World War 2 combat experience showed all participants which ideas in tank design were successful, and which ideas were clearly outdated. In Britain, engineers realized that their infantry tanks were incompatible with modern high-speed maneuver warfare, while their cruiser tanks carried too little armor to be effectively used in assaults against well-defended positions. This led to the formulation of the Universal Tank concept: a tank that would be fast and maneuverable like a cruiser tank, but armored as well as an infantry tank. Because it was easier to increase the armor protection of cruiser tanks already built for speed than to completely redesign the suspensions of slow and inefficient infantry tanks, the universal tank evolved out of existing cruiser tanks. In 1945, the A41 Centurion [16], shown in Figure 7, became the first tank to incorporate these qualities in a unified design. Over the next two decades, the British universal tank concept convergently evolved with the Main Battle Tank, discussed further below, though it was not yet a true MBT, since universal tanks were still intended to be accompanied by newly designed British heavy tanks.

**Figure 7:** A41 Centurion Universal Tank

Airborne combat operations during World War 2 demonstrated a need for light combat vehicles to support paratroopers behind enemy lines. Thus, Western Allied nations that deployed large numbers of paratroopers, including the United States and Great Britain, developed dedicated airborne light tanks that were small enough to fit into large gliders, such as the A17 Tetrarch and the M22 Locust [17] shown in Figure 8. Ultimately, these very light tanks were generally unsuccessful, since the glider payload restrictions did not allow for sufficient armor protection, and many were disabled when their gliders crash-landed. Furthermore, their armament, which was comparable to that carried by regular light tanks of the era, was ineffective against most enemy combat vehicles that they encountered. Russia also experimented with air transport of tanks, though their efforts focused on adapting existing light tanks to be transported under the fuselage of a heavy bomber, which had to land to deploy its tank. These efforts were likewise generally unsuccessful, though efforts in developing truly air-mobile combat vehicles continued throughout the Cold War, as we shall see in subsequent sections.


**Figure 8:** M22 Locust Airborne Light Tank

In addition to conventional light tanks, an even lighter category of tracked combat vehicle was extensively experimented with in Europe during the 1920s and 1930s: the tankette. Tankettes were designed as two-man mobile machine gun nests, the cheapest, smallest possible tracked combat vehicles that could support infantry in local attacks against enemy infantry, or be used for scouting. When used in World War 2, tankettes proved to be vulnerable even to infantry anti-tank rifles and heavy machine guns, so most, like the Polish TKS [18] in Figure 9, were either quickly lost in combat, or withdrawn to perform support duties in the rear. The only nations to successfully operate tankettes in large numbers were Italy and Japan, who used them against the poorly armed populations of Ethiopia and China.

**Figure 9:** TKS Tankette

After World War 2 had ended, all tank categories initially continued to increase in size, firepower, and armor protection. By the 1960s, however, heavy tanks had grown too large to be practical, and medium tanks were exceeding the capabilities of wartime heavy tanks. Thus, it was decided to marry the two categories into the Main Battle Tank (MBT): a tank with the overall hull size and mobility of a medium tank, and the firepower and frontal armor protection of a heavy tank [19], similar to how the British fused their cruiser and infantry tanks into the Universal Tank concept. This was a very successful idea, and since the 1970s, main battle tanks have been the primary combat vehicles of most industrial nations. Incremental improvement of armament and armor, however, has made some modern MBTs, such as the American M1 Abrams, shown in Figure 10, even heavier than many of the heavy tanks of the 1950s and 1960s.

**Figure 10:** M1 Abrams Main Battle Tank

While the general concept of the main battle tank was independently converged upon by British, Russian, and American engineers in the late 1960s, the design criteria differed between the Western and Eastern nations. Western bloc nations, like America, Britain, Germany, and France, ultimately developed heavy MBTs, with large, well-armored, three-man turrets, with ample gun depression, typically around 2.5 meters in overall height and 60 tons in weight. Such tanks were designed to perform best in defensive hull-down positions on elevated terrain features. On the other hand, Eastern bloc nations of the Warsaw Pact focused on developing MBTs that were low to the ground, typically around 2 meters in height, with very small turrets equipped with autoloaders, like the T-72 [20] in Figure 11. These tanks were optimized for offensive operations over flat, open terrain, thus designers primarily sought to reduce the tanks' frontal area, producing tanks that were, on average, around 30% lighter than their Western counterparts, typically around 40 tons.

**Figure 11:** T-72 Main Battle Tank

As main battle tanks supplanted previous medium and heavy tank categories, light tanks continued to evolve as their own class during the Cold War, though multiple attempts were made to fully discontinue this category to leave only MBTs as the sole tank class in service. Many of these new light tanks, like the PT-76 [21] in Figure 12, were amphibious, since their primary intended role was to scout enemy positions and establish bridgeheads at river crossings that could be held while friendly MBTs were transported using pontoons. Thus, their armor protection was necessarily lacking, only sufficient to stop rifle and machine gun ammunition. However, their armament was comparable or superior to that carried by World War 2 medium tanks, which allowed them to destroy most enemy vehicles except for MBTs.

**Figure 12:** PT-76 Amphibious Light Tank

In the 1990s, the first tracked Unified Combat Platforms began to enter service, such as the Swedish CV90 [22] family. UCPs are designed with a standard modular base chassis and a variety of available armor, crew, and weapon modules that can be integrated with the chassis, allowing one manufacturer to offer an assortment of customizable vehicles at comparatively low cost, given their performance. Most tracked UCPs include one or more fire support variants armed with heavy guns, often 105mm or 120mm in caliber, so they effectively fulfill the role of light tanks in modern armies. The one current exception is the Russian Armata heavy UCP, designed to serve as the new primary MBT for the Russian Army [23]. In the T-14 MBT configuration, the Armata is heavier, better armed, and better armored than conventional Cold War era Russian tank derivatives, and may be the first successful example of a new direction in tank design, as more nations standardize their heavy combat vehicles into UCP families.

### *2.2. Armored Cars*

While tanks are the most famous type of combat vehicle to see service in World War 1, they were not the first, having been preceded by the armored car. The first armored cars, like the Austro-Daimler Panzerautomobil [24], were developed as early as 1905, so by the start of the Great War in 1914, most European nations were familiar with the concept. Throughout the First World War, a few hundred armored cars were used to support troops situated near passable roads, primarily by British and Russian forces. Most of these, like the Austin-Putilov in Figure 13, were armed with machine guns, though a few designs, like the Russian Garford-Putilov [25], were armed with light artillery. Armored cars retained an important role after the Armistice, especially within Russia, where considerable numbers were used in the Russian Civil War.

**Figure 13:** Austin-Putilov Armored Car

During the later Interwar Period, armored cars continued to evolve, especially in the Soviet Union, where their range and mobility made them excellent assets in large-scale army exercises. A major focus of Russian armored car development were the medium and heavy armored cars, which carried the same primary armament as contemporary light tanks, often in identical turrets, though they were protected by much thinner armor, due to limitations of automotive suspensions used on the armored cars of the time. Such armored cars were also fielded by Germany and the United States during World War 2, used as scouting, infantry support, and light anti-tank vehicles, capable of much higher speeds than tanks of comparable weight and armament, and generally requiring much less maintenance [26], since wheels are far more resilient than tracks on long-distance travel. Some designs, such as the German SdKfz 234/4 were even armed with main guns used on contemporary medium tanks, in limited traverse mounts, which gave these armored cars excellent firepower for ambush attacks against enemy armored units. An example of a World War 2 medium armored car is the American M8 Greyhound, shown in Figure 14.

**Figure 14:** M8 Greyhound Armored Car

After World War 2, conventional armored cars remained in service with a few nations, primarily as light scouting vehicles, armed with heavy machine guns or light autocannon. The outstanding cross-country mobility of some Cold War armored cars in terrain difficult for heavier tracked vehicles, like sandy deserts and dense jungles, led to the development of armored cars with increasingly powerful armament. Initially, these were intended for infantry fire support, like the FV601 Saladin [27] in Figure 15, and thus carried low-pressure guns which primarily fired high explosive ammunition. These armored cars were, nevertheless, capable of defeating tanks if used properly, since their ammunition included HEAT shaped-charge rounds, whose armor penetration was independent of muzzle velocity, and was generally more than sufficient to defeat the comparatively thin side and rear armor of most contemporary tanks. Some variants of these armored cars were made specifically for the export market, often for Middle Eastern and African nations.

**Figure 15:** FV601 Saladin Armored Car

Since the 1960s, armored cars also took on the anti-tank role more seriously, with European, Far East Asian, and African designs like the Eland 90 [28] (Figure 16) armed with high-velocity 76mm, 90mm, 105mm, and even 120mm main guns. These fast, maneuverable, powerfully armed vehicles remain very popular on the global export market, since they allow nations with limited defense budgets to acquire effective anti-tank assets, which could be used against wealthier neighbors in case of war. The heaviest anti-tank armored cars, like the South African Rooikat [29], Italian B1 Centauro, and Japanese Type 16 MCV, are often referred to as wheeled tanks, since their firepower and mobility match or even exceed those of contemporary light tanks, though their armor protection is generally worse. These heavy armored cars are typically built with an 8×8 drivetrain, weigh around 25 tons, and are capable of road speeds over 100 km/hr, while being armored against armor piercing ammunition up to 25mm in caliber.

**Figure 16:** Eland 90 Armored Car

The first wheeled Unified Combat Platforms preceded their tracked counterparts, entering service and proliferating already in the early 1980s, starting with vehicles like the MOWAG Piranha series, manufactured in Switzerland [30]. These families of combat vehicles likewise use a standard base chassis with a range of available weapons modules, and are typically lighter and cheaper to procure and operate than tracked UCPs. Though the majority of wheeled UCP subvariants are built as troop transports, heavy fire support modules are also available, armed with excellent anti-tank guns, like the M1128 Mobile Gun System [31] in Figure 17. These have steadily been taking on the role of heavy armored cars in many Western nations in recent decades. After seeing the success of such UCPs, some of the older generation anti-tank heavy armored cars, like the Rooikat and Centauro, have retroactively also been converted into limited option UCPs, adapted to carry a variety of turret modules.

**Figure 17:** M1128 MGS Fire Support Vehicle

As the worldwide focus shifted from large-scale open field warfare to localized counterinsurgency operations, often in dense urban environments, a new category of armored car was developed: the internal security vehicle. ISVs, like the M1200 Armored Knight [32] in Figure 18, are primarily designed for low-intensity operations, including urban counterinsurgency, military policing, and precision targeting for friendly air support units. Most ISVs are protected against machine gun and light autocannon fire, grenades, landmines, and high explosive rockets, and are armed with machine guns, though upgrade packages exist for larger low-pressure guns.

**Figure 18:** M1200 Armored Knight

### 2.3. Assault Guns

Although the rotating turret is one of the key design requirements for tanks, it is also a major factor limiting the gun that can be practically used, because:

- The turret and its supporting mechanisms are heavy, and thus take up a significant portion of the weight that can be carried by the tank's suspension
- The turret ring needs to be sufficiently wider than the gun breech block to allow the crew convenient access to load and operate the gun

Thus, if tanks did not need to traverse their armament a full 360 degrees, the same basic chassis could be armed with a much more powerful main gun, and be built much cheaper than a conventional tank. This was considered an acceptable limitation for vehicles intended to support infantry assaults against stationary hostile strongpoints, so the assault gun concept was developed during the late 1930s [33]. Early assault guns were often built using the chasses of medium tanks already in mass production, outfitted with a stationary casemate structure housing a more powerful gun than the parent tank design could carry. The use of pre-existing chasses allowed the development timeline to be shortened and the cost of setting up mass production to be significantly reduced, allowing new vehicles to be fielded within months of being designed. Since assault guns were not intended as anti-tank vehicles, they were often armed with short-barrel guns, firing high explosive rounds at low velocity, as these were sufficient to deal with pillboxes and infantry formations. Furthermore, thanks to the weight saved by removing the turret, the casemate could be protected by thicker frontal armor, improving the survivability of assault guns against enemy artillery: a very important requirement, since these vehicles were used in close proximity to enemy positions. A good example of an early assault gun is the German StuG-3 [34] in Figure 19, used in large numbers during the campaigns in France and Russia, ultimately becoming Germany's most numerous combat vehicle during World War 2.

**Figure 19:** StuG-3 Assault Gun

As the Second World War progressed, German and Russian forces introduced stronger field fortifications, immune to early war assault guns. Thus prompted the development of more powerful assault guns carrying heavy artillery, which could only be carried by heavy tank platforms, like the ISU-152 shown in Figure 20. An unplanned benefit of mounting heavy artillery is that it allowed assault guns to also engage and destroy enemy tanks: though their ammunition had insufficient penetration to destroy well-armored heavy tanks, the sheer impact and blast of high explosive shells weighing over 40 kg was enough to crack armor plates, destroy suspensions, and incapacitate or kill the crew inside. These heavy assault guns were also invaluable during urban assault operations, since they needed just one or two shots to bring down residential buildings used as makeshift fortifications.

**Figure 20:** ISU-152 Assault Gun

After World War 2 had ended, assault gun development went on for a few more years in Russia, building on the experience gained between 1942 and 1945. By this point, however, new heavy tanks under development offered nearly the same firepower as heavy assault guns. New developments in missile technology were also offering more effective solutions against hostile fortifications. Thus, the decision was made to discontinue the development of assault guns as they became redundant.

### 2.4. Tank Destroyers

The desire to equip combat vehicles with larger, more powerful, specialized guns, which led to the development of assault guns, also led to the development of tank destroyers. These combat vehicles were armed with long-barrel high-velocity anti-tank guns, typically smaller in caliber than the main armament of a contemporary assault gun, but with much better penetration against enemy tank steel armor. These guns were likewise much more powerful than the weapons that were fitted to contemporary tanks. The first tank destroyers likewise appeared in the 1930s, and the class was used by every major participant nation in World War 2. Similar to assault guns, tank destroyers were almost always designed using the chasses of tanks already in mass production [35]. Early tank destroyers, however, did not use heavily armored casemates, since they were intended to ambush tanks from long range, and were expected to be safe from returning fire. Thus, open-top tank destroyers with thin armor, sufficient only against machine gun fire, were common, like the Marder 3 Ausf. M [36] shown in Figure 21. The use of thin, lightweight armor also allowed some early tank destroyers to be built using base chasses of halftracks, which were at the time plentiful in the German and American armed forces, though most tank destroyers used fully tracked base platforms.

**Figure 21:** Marder 3 Ausf. M Tank Destroyer

Open top, lightly armored tank destroyers were excellent as ambush vehicles, but they were not able to provide close support for tank assaults against heavily defended enemy positions, and had low survivability if they were caught in the open. Thus, casemate tank destroyers, like the SU-100 [35] in Figure 22, became more common in the final years of World War 2, as combat operations involved larger tank formations, and were often conducted in urban environments. Some of these designs were built as modifications of pre-existing assault guns, so they inherited the thick frontal armor protecting the fully enclosed fighting compartment.

**Figure 22:** SU-100 Tank Destroyer

Most nations built tank destroyers with gun compartments that allowed for very limited gun traverse, to reduce cost and permit use of thicker frontal armor. The one major exception was the US Army, which designed many of its fully tracked tank destroyers with fully rotating turrets [37], like the M10 shown in Figure 23. The lightweight turrets of these tank destroyers were typically open-top, and carried less armor on the sides and rear, which allowed the vehicles to be armed with more powerful guns than contemporary tanks they were derived from, while maintaining the capability of traversing the gun. This design decision was based on the US Army doctrine intended for the Tank Destroyer Force: to serve as an independent army branch, committed to intercept and destroy massed German tank assaults on their own, so that friendly tanks could in turn focus on supporting offensive operations against German positions. In accordance with US tank destroyer doctrine, several purpose-designed tank destroyers were also developed, most notably as the M18 Hellcat (Figure 49). Developing a tank destroyer from the ground up allowed engineers to focus more seriously on high-speed cross country mobility, which was not a major requirement for contemporary tanks, and produce the fastest tracked combat vehicle of World War 2, which served with distinction in Western Europe.

**Figure 23:** M10 Tank Destroyer

After the end of World War 2, a few nations continued to design dedicated conventional tank destroyers, most notably the Soviet Union, which funded development of new vehicles throughout the 1950s. At the same time, the possibility of designing lightweight tank destroyers gained international interest, as these could serve as support vehicles for air-mobile troops operating independently of larger army formations. Such vehicles were developed both in Russia, who produced the ASU-57 and ASU-85, and the United States, who produced the M56 Scorpion and M50 Ontos [38], shown in Figure 24. These tank destroyers had to be light enough to be dropped via parachute from low altitude, and thus could not carry full-size tank guns. Instead, they either carried high velocity guns of relatively low caliber, shortened and lightened derivatives of regular tank guns, or recoilless rifles, as seen on the Ontos, designed to fire high explosive and HEAT shaped charge rounds at low velocity, but producing negligible recoil thanks to the specialized design of the shell casing and gun breech.


**Figure 24:** M50 Ontos Tank Destroyer

The appearance of the first anti-tank guided missiles (ATGMs) in the late 1950s, such as the French ENTAC and SS.10, allowed for the development of much lighter and more capable ATGM vehicles, so traditional gun-armed tank destroyers were eventually withdrawn from service and discontinued development [39]. The late Cold War anti-tank heavy armored cars are sometimes classified as tank destroyers in modern publications, though for the purposes of this study, they remain classified as armored cars only, to avoid double-counting.

### 2.5. Self-Propelled Guns

Combat vehicle classes examined thus far were all intended for frontline combat, either in major offensive operations, or supporting operations on less critical sections of front, so it was critical for them to be protected with adequate armor, especially along the frontal arc, to defend against direct enemy gunfire. That requirement, however, is not as critical for self-propelled artillery vehicles, designed to provide long-range indirect fire support [33]. Self-propelled artillery for indirect fire is generally divided into three categories:

- Self-Propelled Gun (Gun Motor Carriage): armed with long-barrel field artillery pieces
- Self-Propelled Howitzer (Howitzer Motor Carriage): armed with artillery of intermediate barrel length
- Self-Propelled Mortar (Mortar Motor Carriage): armed with very short barrel artillery pieces

This entire class of self-propelled artillery is often collectively referred to simply as “self-propelled guns” – especially since the traditional categories of field guns and howitzers merged into the unified gun-howitzer artillery class in the Interwar Period, with weapons like the Russian ML-20 152mm Gun-Howitzer Model 1937.

The first experiments in using long-range artillery from a combat vehicle were conducted by the British in the 1920s, when they developed the Birch Gun. Many experimental self-propelled guns were subsequently developed in the Soviet Union in the 1930s, as they were expected to be particularly effective in the vast open steppes of Eastern Europe. Most of these designs were built using the chasses of tanks in mass production at the time, as were contemporary assault guns and tank destroyers, since existing platforms were easy to adapt to new roles, and converting them to SPGs was much cheaper and faster than developing completely new vehicles from the ground up. Since self-propelled guns were not intended for direct frontline combat, much of their armor protection was traded for enhanced firepower, producing vehicles armed with much heavier artillery than even assault guns, and the absence of an armored roof allowed for high angles of gun elevation, necessary for long-range bombardment. Once World War 2 began, similar designs were rushed into production by other combatants, such as the US and Britain, like the M7 Priest [40] in Figure 25.

**Figure 25:** M7 Priest 105mm Howitzer Motor Carriage

The most cost-effective self-propelled guns were typically designed to carry artillery up to a caliber of approximately 6 inches, such as the German 150mm, Russian 152.4mm, and American 155mm guns, firing high explosive fragmentation shells around 40 to 50 kg in weight. Larger caliber guns, with even heavier ammunition, are inconvenient or impossible for a crew to load without mechanical assistance. However, this ammunition was insufficient to attack exceptionally strong enemy fortifications, like those encountered by the Germans in Russia, and later by the Allies in Germany, so most nations also developed and fielded small numbers of very heavy self-propelled artillery. Some of these vehicles, such as the 240mm T92 Howitzer Motor Carriage in Figure 26, were also designed using the chasses of existing tanks, but with the chasses lengthened and widened to sufficiently support the large guns. Other vehicles, like the German 600mm Karl Gerat 040, shown in Figure 66, needed to be built on completely new chasses, since no existing platforms were sufficient to handle the weight of the gun and the recoil energy [41]. Such large caliber self-propelled guns were among the heaviest combat vehicles to ever see active service.

**Figure 26:** T92 240mm Howitzer Motor Carriage

While the roles of assault guns and tank destroyers have largely been absorbed by modern tanks, self-propelled guns have remained a major component of ground forces around the world since the end of World War 2. Most of these vehicles continue to be built on tracked chasses, though a growing number of self-propelled guns on wheeled chasses, like the Czech ShKH vz.77 DANA and Swedish FH77BW L52 Archer Artillery System, have been introduced since the 1980s, taking advantage of recent developments in heavy cargo truck design [42]. Thanks to improvements in manufacturing of large turret rings, most modern SPGs, both wheeled and tracks, are built with fully rotating turrets, like the M109 Paladin in Figure 27, which allow them to engage new targets without needing to maneuver the entire vehicle into a new position.

**Figure 27:** M109 Self Propelled Howitzer

Though SPG variants of Unified Combat Platforms are not currently common, they are available, for a selection of both for wheeled and tracked UCPs. The most promising developments in this field are based on heavy tracked UCPs, such as the Armata, which are intended to unify all heavy combat vehicle categories under a single modular platform. An SPG variant of the Armata is currently advertised as under development, though a prototype has yet to be demonstrated to the public. Both tracked and wheeled self-propelled artillery vehicles are recorded as SPGs in this study because their capabilities and design specifications differ significantly from every other combat vehicle class. Also, this study does not examine “mortar carrier” class of vehicles, which are armed with lightweight muzzle-loaded infantry mortars, since they are designed for a very distinctive type of ammunition, and are not directly comparable to conventional guns.

### 2.6. Self-Propelled Anti-Aircraft Guns

The appearance of air power in the early 1900s, and especially the proliferation of bombers and ground-attack airplanes during World War 1, necessitated the development of new anti-aircraft defenses. A major component of anti-aircraft defense throughout the Twentieth Century has been the self-propelled anti-aircraft gun (SPAAG). The first SPAAGs saw service with German, British, French, and Russian troops as early as 1915, built using available cargo truck platforms, armed with “quick-firing” guns (using one-piece cased ammunition) around 3 inches in caliber, such as the German 77mm and Russian 76.2mm. Thus, early SPAAGs were actually comparable in firepower to contemporary tanks, though they did not carry any significant armor protection, and were practically limited to operations on roads, due to the low cross-country performance of early trucks. As aircraft of the 1920s and 1930s became faster and more maneuverable, SPAAG armament became focused on guns of lower caliber, typically between 20mm and 40mm, and considerably higher firing rate, on order of 100 to 200 rounds per minute, with multiple guns firing in the same direction to increase the chance of hitting the target airplane [43]. The M42 Duster shown in Figure 28 is a good example, armed with two 40mm Bofors autocannon.

**Figure 28:** M42 Duster SPAAG

With the beginning of the jet age in the 1950s, crew-aimed SPAAGs proved to be incapable of tracking passing airplanes, and conventional autocannon proved to be far too slow in firing rate to ensure a high probability of hit. Thus, newer

SPAAGs had to be designed, equipped with onboard radars to autonomously track enemy aircraft, predict their flight paths, and aim their guns just ahead of the target to ensure a hit. The fire control systems for these SPAAGs used the most advanced electronics available, and they became among the first military vehicles designed to automatically engage and destroy hostile targets. New autocannons were developed as well, lower in caliber than some that were used commonly in World War 2, but with much higher firing rate and muzzle velocity, to increase the likelihood of impact against a fast jet airplane. The ZSU-23-4 Shilka [43] shown in Figure 29, for instance, was armed with 4 × 23mm guns, which provided a combined firing rate over 3000 rounds per minute.


**Figure 29:** ZSU-23-4 Shilka SPAAG

Jet fighter and ground attack aircraft development progressed rapidly throughout the Cold War, with supersonic combat aircraft already entering service by the 1960s. This meant that SPAAGs had even less available time to engage a passing aircraft while it was within range, so even higher rates of fire and improved accuracy were required [44]. One solution was to use externally powered rotary autocannon, like the M61 Vulcan, already in use on contemporary jet fighters and capable of firing rates over 5000 rounds per minute. The M163 VADS in Figure 30, armed with the M61 Vulcan, is a good example of this generation of SPAAG.

A number of modern SPAAG vehicles, especially those designed in Russia and China, combine modern autocannon with short range Surface-to-Air Missiles (SAM), which allow the composite air defense system to target enemy aircraft that remain outside the conventional autocannon firing range. Classified as Short Range Air Defense (SHORAD) assets, they form the last line of defense against aircraft that were able to evade long range SAM systems. Some of these modern gun-missile SHORAD SPAAGs are also included in this study, but only their guns are recorded for analysis.

**Figure 30:** M163 Vulcan Air Defense System

### *2.7. Armored Personnel Carriers*

The initial purpose of tanks was to open a breach in entrenched enemy defenses that friendly infantry could exploit, without sacrificing hundreds of infantrymen in the process. The slow speed of World War 1 tanks, and the relative proximity of enemy trenches, meant that infantry could easily catch up with their tanks when necessary. However, there was still a risk of losing advancing infantry to artillery bombardment and unsuppressed machine gun nests, even if tanks were able to open a breach. Thus, already during the Great War, British engineers were considering means to deliver infantry directly to the enemy position without exposing them to enemy fire on the way. Thus, the concept of the armored personnel carrier (APC) was born, with the first such design produced as the Mark 9 “tank” by the British in 1918, though it did not see service in its intended role. The Interwar Period saw limited development of the subject, with only Germany the United States, and Great Britain fielding early APCs in significant numbers during World War 2, most of them open-top halftracks, like the German SdKfz 251 and the American M3 / M5 series [45] shown in Figure 31. These halftrack APCs could typically carry a squad (around 10 to 12 infantrymen) who fought dismounted, and could provide limited fire support with a single machine gun.

**Figure 31:** M3 Halftrack Personnel Carrier

The island hopping campaign waged by the United States in the Pacific Theater of Operations required urgent development of amphibious troop carriers, which could be used by the Marines during amphibious assaults against islands occupied by Japanese troops. Conventional boat landing craft were unable to pass through coral reefs and sandbars of atolls like Tarawa, and were unable to deliver any combat vehicles to support the Marines after landing. Thus, the LVT series of tracked landing vehicles was designed, the world's first amphibious APCs. Most World War 2 LVTs, such as the LVT-4 shown in Figure 32, were designed to carry two squads of Marines (24 men), and were armed with multiple machine guns for fire support [46]. As machine guns alone were insufficient to destroy Japanese coast defense pillboxes, a series of better armored fire support LVT(A) designs was developed, armed with turrets from contemporary light tanks, intended to support the Marines as they pushed deeper inland to establish a defensible beachhead. These LVTs were necessarily much larger than purely land-based personnel carriers, but they fulfilled the same role, of delivering troops to a combat zone.

**Figure 32:** LVT-4 Amphibious Landing Transport

World War 2 combat experience decisively demonstrated the need for fully armored troop carriers, as combat operations were now much more rapid and intense than had been anticipated by military planners prior to 1939. Thus, the first modern APC was born when US engineers developed the M44 (T16) in 1945, using the base chassis of the M18 tank destroyer. This APC was a relatively light combat vehicle, sufficiently well armored to protect the troops inside from heavy machine gun fire, sufficiently fast to keep up with the tanks, and sufficiently large to hold two infantry squads, like the amphibious LVTs. However, Army strategists realized that it would be a large target for enemy fire, so subsequent APCs, like the M75, M59, and the famous M113 [47], shown in Figure 33, were designed to carry just one squad, with 10 to 14 seats depending on the design. Formally, these APCs were intended to deliver infantry to a combat zone like a "battlefield taxi" and recover the troops after battle, but would often support their infantry using machine guns in combat.

**Figure 33:** M113 Armored Personnel Carrier

While a significant fraction of APCs designed during the Cold War were based on tracked chasses, many contemporary APCs of Russian origin used wheeled chasses, like the BTR-60 [48] shown in Figure 34. The advantages offered by wheel-based locomotion include reduced manufacturing costs, ease of maintenance, improved fuel efficiency, and ease of driver training. Since traditional APCs were not intended to carry powerful armament or heavy armor, wheeled chasses worked exceedingly well for the role, with recent derivatives like the BTR-90 still in service with Russian, Belorussian, Ukrainian, and other Eastern European armed forces. Many of these wheeled APCs have firing ports in the passenger compartment, so that the infantry can engage enemy forces from inside the vehicle, and add to the APC's own firepower, typically consisting of just one machine gun in a small turret.

**Figure 34:** BTR-60 Armored Personnel Carrier

Both wheeled and tracked Unified Combat Platforms were discussed earlier, since their heavy fire support subvariants are effectively equivalent to light tanks and heavy armored cars in modern service. The majority of UCP variants, however, are configured as troop carriers, integrated with modules that can usually hold 8 to 14 infantrymen in the APC role, depending on the specific platform and module. Most wheeled UCPs were initially marketed as modular APCs when introduced, including the Swiss MOWAG Piranha, Finnish Patria AMV, and German ARTEC Boxer. The MOWAG Piranha, the first UCP to become popular on the global defense market [30], has evolved into a very large family of derived UCPs since its introduction in the 1970s, including the Canadian AVGP, LAV-2, and LAV-3, the Australian ASLAV, as well as the more famous American Stryker [31], shown in Figure 35. In the APC configuration, these vehicles typically receive minimal armament, often just one machine gun, although automatic grenade launchers can also be used if more firepower is required for a mission. Modern UCP APCs frequently have the machine gun mounted in a remote weapon station with integrated optical and thermal cameras, so the gunner can remain safely inside the vehicle when engaging the enemy, and has better situational awareness at night. Tracked UCPs, such as the Swedish CV90, are configured as APCs more rarely than are wheeled UCPs, and are likewise lightly armed, to allow for high infantry capacity.

**Figure 35:** M1126 Stryker ICV

In recent decades, a specialized class of APC has also become popular on the global market: the MRAP (Mine-Resistant Ambush-Protected). This class of vehicles evolved out of mine-resistant troop transports developed by the Rhodesian Army in the 1970s, like the Hippo, Buffel, and Casspir [49]. Since its introduction in 1980, the Casspir has become the basis for most subsequent MRAP development, as it consolidated the key defining features of the class:

- Main body raised high up off the ground
- Body built with a V hull to deflect landmine shock waves away from crew and infantry
- Wheel assemblies designed to break away in an exceptionally large land mine detonation to protect vehicle occupants
- Entire body armored against heavy machine gun fire, bomb blast, and shrapnel

MRAPs saw widespread global use after US and Coalition forces began to suffer high casualties from roadside IEDs during the Second Gulf War of the early 2000s. In response, around a dozen companies in the US alone began production of MRAP APCs, most using available commercial trucks as base chasses, equipped with armored V hull bodies. Several designs out of South Africa also saw success on the global market, like the RG-33 shown in Figure 36. Most MRAPs are designed to carry 8 to 12 infantrymen, and are armed with one machine gun or an automatic grenade launcher.


**Figure 36:** RG-33L MRAP

## *2.8. Infantry Fighting Vehicles*

While APCs have been an indispensable constituent of land armies since World War 2, their official design objective was only to deliver infantry to and retrieve infantry from a combat zone. Thus, the armament they carried was minimal, primarily intended to engage enemy infantry and unarmored vehicles in self-defense, since integrating heavier weapons would shrink the passenger compartment or increase vehicle weight. Furthermore, their armor protection was likewise minimal, typically only intended to stop incoming machine gun fire. Thus, while many APCs did provide machine gun support to their infantry when they could, they had negligible survivability in a major assault against well-defended enemy positions. This meant that only the tanks could accompany infantry on offensive operations. By the late 1950s, however, tanks not only had to engage enemy tanks and armored cars, but also light vehicles and infantry armed with long-range ATGMs, which could not be easily countered by regular foot soldiers. These factors necessitated the development of a new class of combat vehicle, which could both carry infantry and provide adequate fire support, both for friendly infantry and friendly tanks, during a major offensive operation. Thus, the concept of the infantry fighting vehicle (IFV) was born. The first IFV was the HS.30, designed in Germany in 1958, followed by the Russian BMP-1 in 1966 [50], shown in Figure 37. IFVs typically have lower troop capacity than do APCs, typically carrying just 6 to 9 passengers. Their armament, however, is considerably more effective: most IFVs are armed either with an autocannon 20mm to 30mm in caliber or a low pressure gun of greater caliber, typically mounted in a turret larger than those used on APCs. Many IFVs also carry a small number of ATGMs, to allow them to destroy enemy tanks if friendly tank support is not available.

**Figure 37:** BMP-1 Infantry Fighting Vehicle

As was seen with the development of MBTs, engineers of Western and Eastern nations took different approaches to the design of IFVs. Traditional Eastern bloc IFVs, like the BMP-1, BMP-2, and their derivatives, were built low to the ground to reduce their frontal area, much like the MBTs they supported, since they were intended for large-scale offensive operations over the flat, open terrain of Eastern Europe. Thus, these IFVs were typically around 2 meters in height at the turret roof. Western bloc IFVs, by comparison, such as the M2 Bradley [51] shown in Figure 38, are typically much taller, around 3 meters in height. Several factors contribute to this: the infantry compartment is built taller, to be more comfortable for the passengers, there is more ground clearance, for improved performance over rough terrain, and there is a much larger two man turret, providing the commander with a better view of the battlefield, often equipped with an extensive array of sensors.

**Figure 38:** M2 Bradley Infantry Fighting Vehicle

One special class of IFV was developed in Russia at the end of the 1960s: the airborne fighting vehicle [52]. These IFVs, like the BMD-2 in Figure 39, were built to be paradropped out of cargo aircraft to support paratroopers on the ground. To reduce the weight of the vehicle, while maintaining sufficient space for 4 crewmen and 4 paratroopers, these vehicles were built out of lightweight aluminium alloy armor, thick enough to stop machine gun and rifle fire. The resulting vehicles became the lightest IFVs on record, weighing just 7 to 8 tons. Their armament, however, was equivalent to the BMP series of conventional army IFVs, consisting of either a 73mm low pressure gun or a 30mm autocannon on most variants.

**Figure 39:** BMD-2 Airborne Fighting Vehicle

Of course, Unified Combat Platforms have also been an important area of IFV development in recent decades. The first tracked UCP, the Swedish CV90 [22], was initially advertised as a modular IFV, equipped with a very large two man turret armed with the Bofors 40mm autocannon, with sufficient space to carry 8 infantrymen. Most CV90 derivatives are also IFVs, configured to the requirements of foreign buyers, often armed with 30mm or 35mm autocannon more commonly used by other Western nations. Other tracked UCPs, such as the Russian Kurganets 25 UCP and the Armata heavy UCP [23], also offer IFV variants. The T-15 Armata IFV, for instance, offers the same level of protection as its T-14 MBT counterpart, probably making the T-15 the best-protected IFV in the world at this time. Similarly, some outdated Cold War MBT designs have retroactively been converted into heavy UCPs with IFV variants, like the Ukrainian BMPV-64 heavy IFV, based on the T-64 MBT.

While wheeled UCPs are most often configured as lightly armed APCs, a small selection of IFV variants are also available. The first wheeled IFV was the South African Ratel, developed in the 1970s [49]. Several turret modules were available for the Ratel, armed either with autocannon or with light anti-tank guns, but it was not yet a fully modular UCP, since all variants shared the same overall hull structure, and only offered a selection of turret modules. By the late 1980s, IFV variants of fully modular wheeled UCPs were becoming available, such as the LAV-25, one of the many Canadian derivatives of the MOWAG Piranha series [30]. Since these vehicles proved to be very effective, many more UCP IFVs were developed through the 1990s and 2000s. Most of these IFVs can easily be differentiated from their APC counterparts by the presence of a large, often two man turret, similar to the turrets used on conventional Western IFVs. Primary armament typically consists of a 25mm, 30mm, or 35mm autocannon.

### *2.9. Vehicle Categories not Covered*

This study is focused on the historical analysis of armored fighting vehicles armed with conventional guns, capable of independent cross-country locomotion. Therefore, many categories of combat and combat support vehicles have to be necessarily omitted, to limit the overall scope.

Vehicle categories not included in this study:

- Vehicles limited to railway locomotion:
  - Armored trains
  - Armored draisines (independent motorized armored railcars)
  - Railway specific derivatives of conventional wheeled vehicles (e.g. armored cars / APCs)
- Vehicles armed with rockets or missiles:
  - Multiple rocket launchers
  - ATGM vehicles
  - SAM vehicles
  - Tactical nuclear missile vehicles
  - Cruise missile vehicles
  - ICBM vehicles
- Vehicles with alternative main armament
  - Mortar carriers (armed with standard infantry mortars firing fin-stabilized mortar bombs)
  - Flamethrower vehicles
- Combat support vehicles (unarmed)
  - Amphibious transports
  - Bridging vehicles
  - Combat engineering vehicles
  - Command vehicles
  - Electromagnetic warfare vehicles
  - Medevac vehicles
- Unarmored / unarmed logistics vehicles:
  - Tactical trucks / tractor units
  - Light utility vehicles (e.g. Jeeps)
- Improvised fighting vehicles
  - Technicals (weaponized civilian cars)
  - Gun trucks

## 3. DATA ANALYSIS

### *3.1. Introduction*

Data for this study was primarily collected from online encyclopedic sources, such as the Tanks Encyclopedia [53] and Wikipedia, which in turn are sourced from publicly available published books on tank history, including work by David John Fletcher, Michael Guardia, Richard Pearce Hunnicutt, Richard Ogorkiewicz, and Dr. Steven Zaloga. Additional data was collected from public brochures released online by major defense manufacturers, such as BAE Systems, General Dynamics Land Systems, Krauss Maffei Wegmann, and Uralvagonzavod, advertising the capabilities of their combat vehicles, as well as informational handbooks published by the Jane's Information Group.

The total population examined in this study consists of 1277 individual vehicles, including prototype vehicles that never entered service and mass-produced vehicles that saw active service. Theoretical project vehicles that never left the drawing board were not included in the study, since real performance almost always falls short of initial predictions and ideal design goals. Vehicles in the examined population originate from over 40 different nations, with the largest sets from Russia, the United States, Germany, Britain, and France.

Each vehicle had up to 49 details recorded (as available) in a standardized table. These included:

- Name, country, year, category, reference link
- Vehicle dimensions and weight
- Armor thicknesses on hull and turret surfaces
- Details on primary armament / secondary armament / machine guns
- Power and mobility capabilities

Once collected, the data was subsequently analyzed using Wolfram Mathematica V.12.1, with the results presented in charts below. Most of the charts are color-coded by the 8 categories of combat vehicles examined in the study, to provide a cohesive understanding of the selected vehicle classes and their evolution. To save on space used by plot legends, the following color-coded acronyms are used in the plots instead of full category names:

- **T** (Tanks)
- **AG** (Assault Guns)
- **TD** (Tank Destroyers)
- **AC** (Armored Cars)
- **SPG** (Self Propelled Guns)
- **IFV** (Infantry Fighting Vehicles)
- **APC** (Armored Personnel Carriers)
- **SPAAG** (Self Propelled Anti-Aircraft Guns)

Around one third of the plots use alternative color schemes. A selection of plots focused on analyzing vehicle mobility by comparing different systems of locomotion are shown color-coded by the method used (track / wheel / halftrack). Plots focused on an overall analysis of gun performance are color-coded by the type of gun used, to demonstrate that the observed trends are largely uniform across the entire spectrum of modern guns. Plots focused on analysis of armor penetration are color-coded by the specific type of armor-piercing round.

### 3.2. History of Development

We begin with an analysis of vehicle development rates, and their evolution over a century of combat vehicle design. Figure 40 very clearly shows several overarching historical themes that we will also see repeated in most other historical plots presented in this study, so these are discussed up front. The first major spike in development and experimentation falls between 1915 and 1920, during World War 1, and primarily features developments in the first tanks and early armored cars, as well as primitive truck-mounted SPAAGs.

Following a 5 year long lull in development, there is an increasingly intense 20 year period of widespread international experimentation between 1925 and 1945, peaking during World War 2, 1940 to 1945. These two decades see continued experimentation in tank and armored car design. This is also the only historical period when assault guns are developed and used in appreciable numbers, and the richest period for experimentation with tank destroyers. SPGs and SPAAGs gain considerable variety at the end of this period, during World War 2. The first APCs also appear during this time and proliferate during WW2, most famously the German and American halftrack APCs.

After the war, there is a considerable reduction in yearly developments, with the rate of introduction for new prototype and production designs remaining persistently low after 1945. The dominant classes developed between 1945 and 1965 are tanks, TDs, SPGs, and APCs. The first IFVs join in 1965 and remain a relatively significant component of combat vehicle innovation since. This striking reduction in innovation of new combat vehicles has several reasons, both reflecting the real world situation, as well as the quality of available data.

After the end of the War, nations could not afford to dedicate nearly as much funding to the development and production of perpetually innovative combat systems, since a wartime economy is not sustainable in the long term, and many nations were practically ruined by the war, especially Germany, Russia, Japan, Italy, France, and Great Britain, who needed to focus on internal nationwide restoration. Furthermore, even after national economies were rebuilt, and funding could be allocated to the development of new military equipment, the process of development itself became considerably longer. Modern combat vehicles are far more complex engineering projects than their predecessors in the 1940s. Throughout the Cold War, there was an increasing amount of electrical and electronic equipment integrated on military vehicles, including sensors, analog and digital computers, motors to control fine turret movement and gun elevation, autoloaders, all of which take time to develop, perfect, and produce. Newer materials were being introduced, including steel and aluminium alloys for primary armor, armor ceramics and bulletproof glasses, some of which required involved post-production treatment cycles before assembly. Thus, unsurprisingly, the rate of development of new combat vehicles had been drastically reduced.

The observed reduction in new developments, however, is also in part due to an inherent bias in the available data. Archival information about combat vehicles developed prior to the 1960s is, more or less, fully declassified and available to professional historians writing books for popular readership, while more recent developments, especially since the 1980s, are more sensitive, and thus, considerably less thorough information is available for public release. Thus, while we are aware of dozens of individual prototypes developed within a particular overarching R&D program during the World War era, information on similar stepwise developments of the later Cold War is more difficult to find, beyond a brief mention of a specific prototype name alluded to in a particular book. Furthermore, there is a great public interest in the topic of World War 2, and the many developments that led up to it, so more historians are motivated to examine the available documentation on the topic, since it will sell more books. Thus, the histogram in Figure 40 must be understood in its proper context: while the overall rate of development had been significantly reduced after 1945, it was not actually as low as it appears to have been from the data currently available.

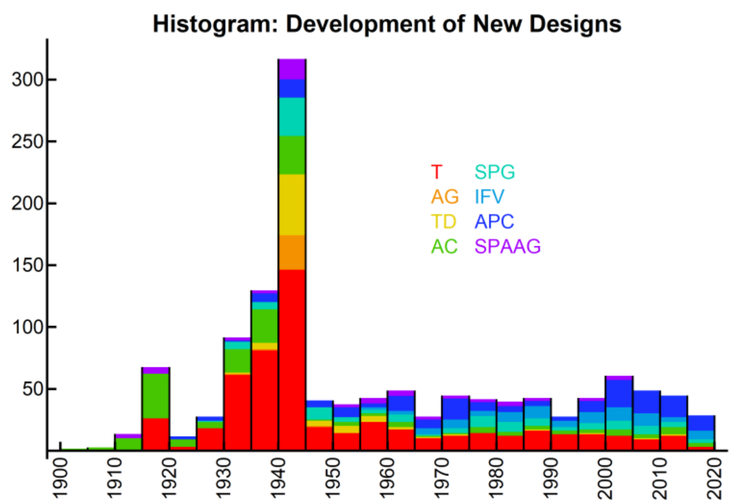


**Figure 40:** Numbers of new combat vehicle types developed worldwide in each half decade between 1905 and 2020

### 3.3. Vehicle Size

Next, we examine historical trends in vehicle weight, as seen in Figure 42. This plot represents vehicles between 1 and 200 metric tons in weight, to best show the major trends in the data. A few lightweight outliers are therefore not represented, since their weight was significantly below 1 ton, and representing them reduced the clarity of the rest of the dataset. These outliers included an ultralight tank destroyer converted from a moped, the French Vespa 150 TAP, as well as several experimental robotic combat systems developed recently.

Significant variability is observed in the weights of tanks prior to 1945: this is because the category of tanks in this study includes light, medium, and heavy tanks, as well as tankettes (very light machine gun tanks used for scouting and infantry support) and superheavy tanks. Most tanks designed between 1925 and 1945 fall between 10 and 50 tons, though a few designs (many of which were purely experimental) measured between 50 and 85 tons, and one, the German PzKpfW 8 Maus, shown in Figure 41, weighed an incredible 188 tons, the one superheavy tank project to be developed to full prototype stage. Following World War 2, the weight range for most tank designs shifts upwards, to between 35 and 70 tons, and this range remains consistent for the Cold War and the Modern Period. The very light tankettes go extinct during the War, as do the superheavy tank designs, since they have been shown to be impractical in use, and thus, a waste of resources. Light tanks do remain, but are designed rarely, since the class had been declared "obsolete" on multiple occasions since the appearance of main battle tanks. It is also important to note that all plots in this study only track the initial appearance of a particular vehicle, and do not reflect the duration it has remained in service worldwide, thus, while many tanks designed in the 1960s and 1970s still remain widely in service with Third World nations, only their initial introduction to service is recorded.

**Figure 41:** PzKpfW 8 Maus Superheavy Tank

The majority of armored cars designed during the World War era weighed under 10 tons, likely because automotive suspensions of the time could not handle greater weights, even on 3 axle chasses, while designs with more than 4 axles were not practical to use. Modern automotive suspensions do enable more massive armored cars, but the class has been largely supplanted by APCs, which are also able to act as scouts if necessary. Thus, in modern service, only the heavily armed anti-tank armored cars and heavy fire support UCP subvariants still fulfill the traditional the armored car role.

APCs of the Cold War and the modern period have generally remained stable between 10 and 15 tons in weight, though some heavier outliers exist. These are often the large amphibious APCs, like the LVTP-5 and AAVP7 amphibious assault vehicles, with high troop capacity to ensure efficient transport of infantry units or even light combat vehicles across large bodies of water.

The predominantly tracked IFVs and SPGs generally fall between the tank and wheeled APC weight categories. For IFVs, this is due to the lack of a large tank-style turret and large-caliber main gun, combined with armor thicker than used on APCs, but much thinner than tank armor, while for SPGs, this is due to the use of minimal armor protection, even though a large main gun is carried, often in a turret on modern SPGs.

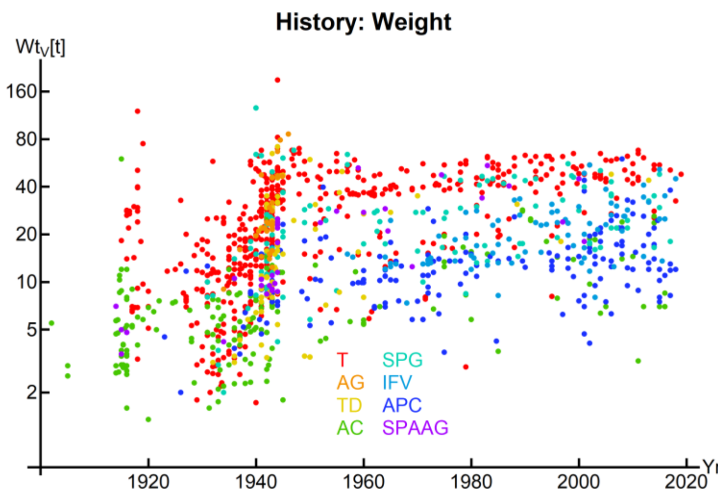


**Figure 42:** Historical evolution of the combat weight of armored fighting vehicles, in metric tons

Extensive design experimentation between 1925 and 1945 is also evident in the plot of vehicle hull lengths, Figure 43, with the majority of combat vehicles of all classes ranging from just over 2 meters to almost 8 meters in length. By 1960, this overall range shrinks to between 4 and 7 meters, with subsequent gradual increase in length to between 5 and 8 meters by 2010. The very long outliers in the Cold War / modern era include large amphibious APCs as well as wheeled SPGs based on commercial cargo truck platforms, which have become popular since the 1980s, such as the vz.77 DANA. These SPGs make excellent use of the length of modern heavy trucks, carrying large ammunition supplies and robust integrated autoloaders. Very long outliers in the World War 1 era are experimental heavy tanks, designed to be able to cross wide trenches in massive tank assaults tentatively planned by both the Allies and the Central Powers for 1919. Exceptionally short outliers, on the other hand, include unique, highly unconventional designs, such as the experimental Kugelpanzer (Figure 44), developed in Germany in 1945, and the Vespa 150 TAP, a 1956 French moped armed with a 75mm recoilless rifle, issued to French paratroopers. Such designs have generally been considered dead ends, which is why they remain unique in the historical record.

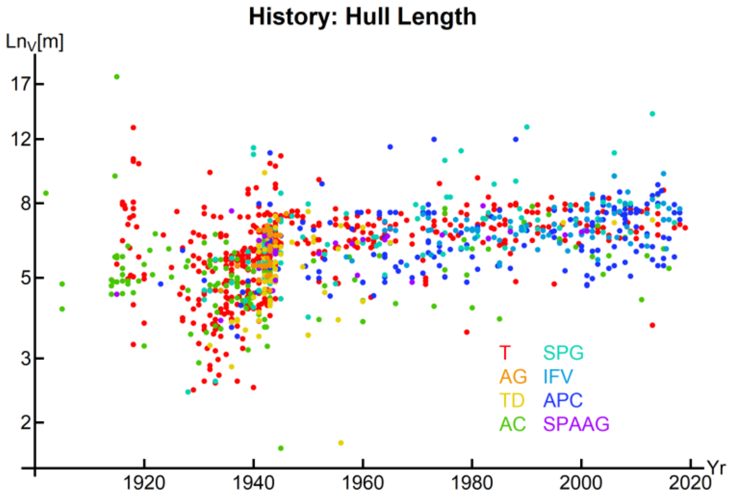


**Figure 43:** Historical evolution of combat vehicle hull length in meters

**Figure 44:** Kugelpanzer Experimental Vehicle

The plot of hull widths in Figure 45 likewise demonstrates extensive experimentation between 1925 and 1945, and reveals a stronger separation between tracked platforms and wheeled platforms. Most tracked vehicles developed after 1945, including tanks, SPGs, and IFVs, generally have hull widths between 3 and 4 meters, while wheeled vehicles, including armored cars, APCs, and wheeled SPGs, generally lie between 2 and 3 meters. This can largely be attributed to the fact that wheeled vehicles are typically designed to be able to use standard roads and highways, which vary from 2.5 meters to 3.5 meters, depending on nation, while tracked vehicles are typically transported on trailers to their destination, to avoid wearing out their tracks, and to avoid damaging national roads. The great width of some World War 1 designs can be attributed to the side gun sponsons used on most British tanks of the Great War. The wide outlier of the World War 2 era is the US Army T28 Super Heavy "Tank" (also called the T95 105mm GMC), an experimental superheavy assault gun developed to destroy German fortifications. Vehicles more than 4 meters in width have been rarely built due to the associated difficulty with transportation: the aforementioned designs of excessive width had to be disassembled whenever being transported by rail, which limits strategic mobility significantly.

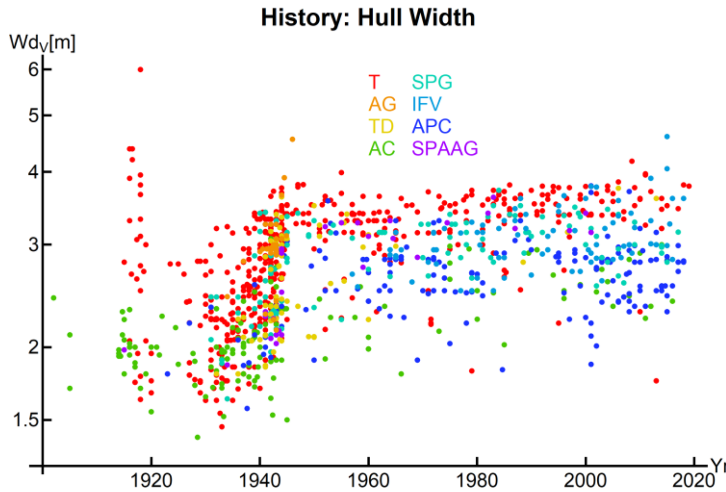


**Figure 45:** Historical evolution of combat vehicle hull width in meters

The plot of hull length-to-width ratio, in Figure 46, shows that the majority of designs have always generally remained between 1.5 and 3, even during the two experimental decades. Since 1960, most tracked vehicles (tanks and IFVs) have generally had hull length-to-width ratios between 1.5 and 2.5, most likely because this range offers the best maneuverability for vehicles designed for differential steering. Meanwhile, contemporary wheeled vehicles (primarily APCs and armored cars) have had hull ratios between 2.5 and 3, likely a consequence of both the limitation on their width and their capacity for explicit steering of individual wheels. Once again, the long SPGs based on commercial heavy trucks are notable outliers, due to their great hull length.

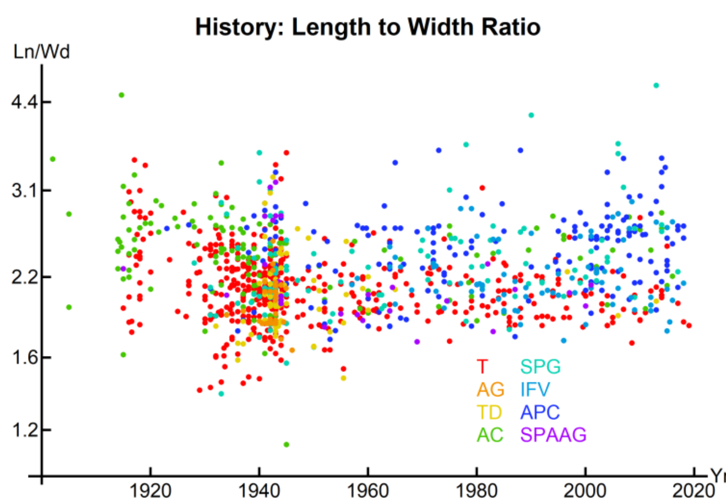


**Figure 46:** Historical evolution of the length to width ratio of the hulls of combat vehicles

### *3.4. Vehicle Mobility*

The plot of engine power output in Figure 47 shows a wide range of engines used during the experimental decades, and overall standardization of designs after 1960, as the preferable weight ranges for tanks, APCs, and other vehicle classes became well defined. In the Cold War and modern era, tank engines have generally fallen between 500 and 1500 horsepower, while engines between 150 and 600 horsepower have generally been used for wheeled APCs and armored cars. Engines developed for tracked SPGs and IFVs overlap with low-power tank engines and high-power APC engines, as their weights likewise lie between the weights of tanks and APCs.

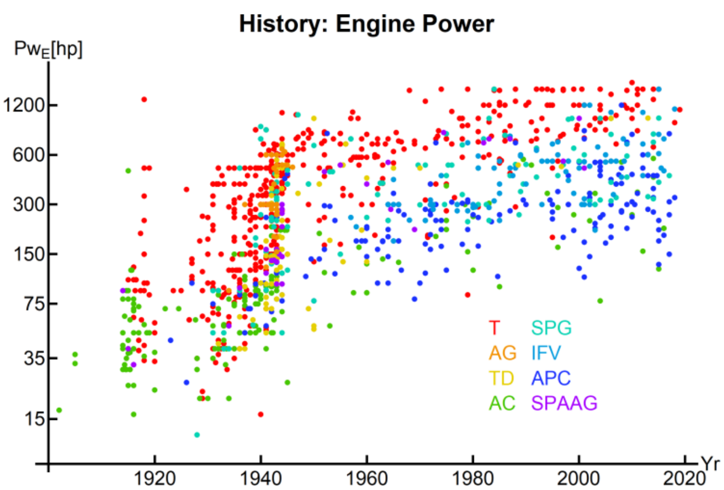


**Figure 47:** Historical evolution of engine power output of combat vehicles, in horsepower

A more uniform cross-category trend is observed when examining the history of power-to-weight ratios, shown in Figure 48. In the period between 1960 and 2020, there has been an overall increase in power-to-weight ratio, with most vehicles in 1960 falling between 12 and 24 hp/ton, while in 2010, most designs were between 18 and 30 hp/ton. This increase is largely due to perpetual development in automotive and aviation engine design, with the best available solutions ultimately adopted for military vehicle engines. Furthermore, this plot demonstrates that improvements in mobility are, in fact, a major driving factor of vehicle design. If armament and armor were much more important than mobility, we would have expected to see a generally flat trend throughout the Cold War and Modern Period, as vehicles would have been made as heavy as possible, as long as their engines could support a baseline level of mobility. However, the increasing power to weight ratio, even among tanks, shows that combat vehicle designers perpetually seek to improve mobility, which is of paramount importance for military doctrines emphasizing rapid, large-scale army maneuvers. Mechanized warfare has dominated military strategic thought of the past century, first proposed by J. F. C. Fuller in his Plan 1919 strategy, and subsequently expanded upon by Vladimir Triandafillov, in his doctrine of Deep Offensive Operations, and Heinz Guderian, who adapted the German concept of Bewegungskrieg (maneuver warfare) to modern armor formations.

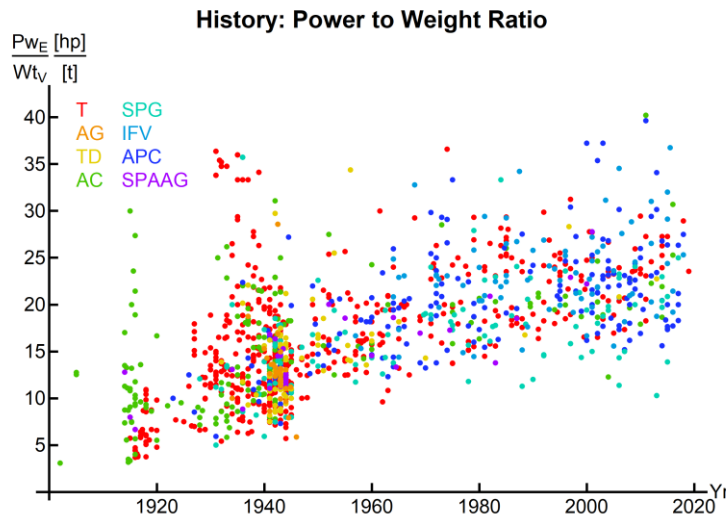


**Figure 48:** Historical evolution of the power to weight ratio of combat vehicles, in horsepower per ton

The steady increase in engine power to weight ratio in the last 60 years has allowed for much greater maximum road speeds, for tracked and wheeled vehicles alike. By the end of World War 2, most tracked vehicles (tanks, assault guns, and TDs) had maximum speeds between 30 and 60 km/hr, though there were a few exceptions, most notably the M18 Hellcat tank destroyer (Figure 49), specifically designed for high speed attacks against German tank formations, with a road speed in excess of 80 km/hr. Contemporary wheeled vehicles (primarily armored cars) had maximum road speeds between 60 and 100 km/hr, though their cross-country mobility suffered much greater reduction than that of tracked vehicles.

The presence of tanks in the armored car speed range during the 1930s needs to be explained: these were the road speeds of wheel-track tanks that relied on the Christie suspension, primarily the Russian BT series of fast tanks. These tanks were designed to be able to travel along roads on their wheels directly, to increase their speed when deploying to the front, so two independent road speeds are recorded and shown for these tanks, one in wheeled mode, one in tracked mode. In wheeled mode, the tracks of the tanks would be removed, and the engine would drive the rear wheel of the tank itself. While this method did allow for considerably higher road speeds, the tank then needed to have its tracks reinstalled for cross-country driving, which was a time consuming process, and was only practical for very light tanks with narrow treads. Thus, the practice was discontinued when combat conditions began to require much thicker armor, which dramatically increased vehicle weight and necessitated the introduction of wider and heavier tracks.

**Figure 49:** M18 Hellcat Tank Destroyer

Since the end of World War 2, road speed envelopes have gradually climbed upward, with tracked vehicles (tanks and IFVs) reaching maximum road speeds up to 60 to 80 km/hr by 2010, while maximum road speeds for wheeled vehicles (APCs and armored cars) generally range between 85 and 110 km/hr. It is important to note, however, that these are maximum speeds on smooth, flat, paved roads, and that practical cross-country speeds on rough terrain are always much lower, even for modern vehicles built with much more capable drivetrains. It should also be noted that these maximum speeds are often determined by the vehicle's integrated speed governor, set at some nominal maximum value to protect the drivetrain and suspension against vibration damage. Thus, for most vehicles since World War 2, absolute maximum speed that could theoretically be achieved on a paved road at maximum engine power output would be even higher than those quoted here.

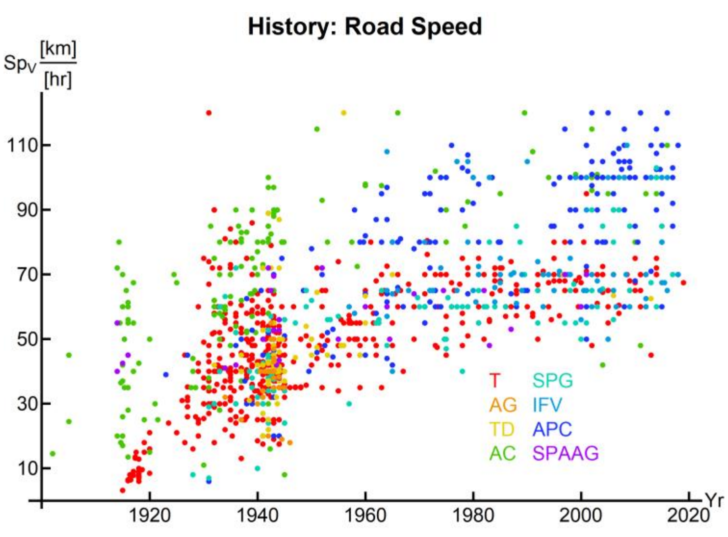


**Figure 50:** Historical evolution of combat vehicle maximum driving speed on flat, paved roads, in kilometers per hour

This study does not include an analysis of cross-country speeds, for a few reasons. Most importantly, many of the vehicles in the database did not have any available data on cross-country speed, and the dissimilar testing protocols used in different nations make it challenging to compare cross-country performance of their vehicles directly even when data is available. Furthermore, some vehicles in the dataset were designed for different modes of locomotion on road vs. cross-country, for instance, the wheel-track Christie suspension tanks mentioned earlier, which could drive on roads on their wheels directly, and drive cross-country once their tracks were installed. A number of Cold War armored cars, like the French Panhard EBR (Figure 51) or the Russian BRDM, for instance, had auxiliary wheels, which were raised up off of the ground for high-speed driving on paved roads, and were lowered down to the ground for improved traction and reduced ground pressure on cross-country terrain. There were even vehicles which had a short set of tracks between their major driving wheels, fulfilling the same purpose, including a few experimental light tanks of the Interwar Period, such as the British Vickers D3E1, and experimental IFVs of the Cold War, such as the Russian Object 19. Collectively, these are referred to as "wheel-cum-track" vehicles. Thus, the cross-country performance of these rare vehicles is not directly comparable to that of conventional vehicles.

**Figure 51:** Panhard EBR Armored Car

Available data on power-to-weight ratios and maximum road speeds allows us to produce a plot that compares the overall power efficiency of wheeled and tracked locomotion, shown in Figure 52, as well as a histogram of the (speed) / (power-to-weight) ratio, shown in Figure 53. From the initial plot, we can quickly see that given the same power-to-weight ratio, a wheeled vehicle will generally be faster than a tracked vehicle, though there is some overlap between the efficiency ranges of these categories. Calculating the average slope for each locomotion category, we observe that tracked vehicles on average get around 2.96 [km/hr] per [hp/ton], with a standard deviation of 0.67, while wheeled vehicles get around 4.71 [km/hr] per [hp/ton], but with a much larger standard deviation of 1.29. This discrepancy between wheeled and tracked vehicles is not surprising, since continuous track systems are expected to have much higher energy losses, due to friction between components, inefficiencies in the complex drivetrain, reduced shock mitigation at high driving speed, and considerable weight of the continuous tracks themselves.

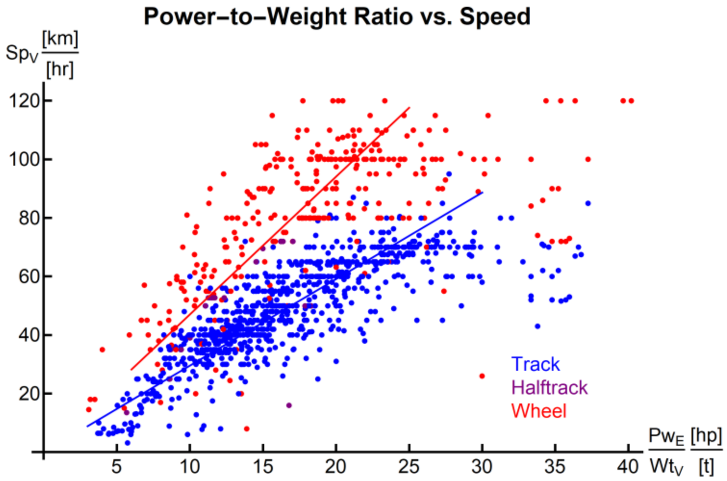


**Figure 52:** Relationship between the power to weight ratio, in horsepower per ton, and paved road speed, in kilometers per hour, for combat vehicles using different mobility systems

It is possible that the larger standard deviation observed for wheeled vehicles is due to the relatively small sample size used in this study: out of the 1277 vehicles examined, only 348 were wheeled, while 900 were tracked. Also, it is possible that the greater standard deviation reflects differences design philosophy, with some engineers choosing to use a much higher factor of safety in engine power, to allow their wheeled vehicle to accelerate faster in an emergency, or have better performance on slopes and rugged terrain, resulting in a lower apparent power efficiency on flat paved roads, while other engineers used a lower factor of safety for engine power, perhaps to reduce the overall vehicle size and weight, or because their wheeled combat vehicles were derived from conventional civilian models, already being produced with a reliable engine, whose original factor of safety was effectively used up by the increased weight of armor.

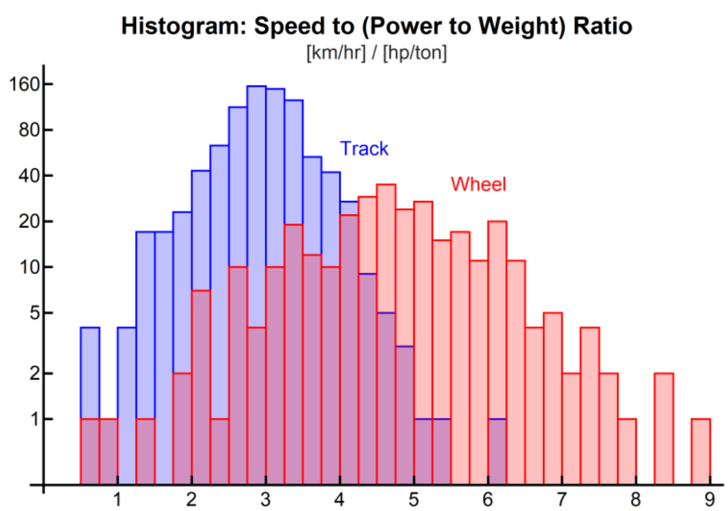


**Figure 53:** Histograms of combat vehicle power efficiency, in (kilometers per hour) per (horsepower per ton), comparing tracked and wheeled combat vehicles

Historical variation in power efficiency is examined in Figure 54. The pattern observed in tracked vehicles, particularly tanks, is not surprising, showing a low initial efficiency observed for World War 1 designs, a relatively constrained distribution of efficiencies in the 1925 to 1945 period, and a narrow band after World War 2. This narrow band indicates that designers of tracked armored fighting vehicles may have reached a practical limit for power efficiency with technologies available up to the present day. As such, this limitation may represent one of the key opportunities for future technological growth: to develop tracked vehicle drive trains with higher power efficiency, which would be robust enough and cheap enough to be practically used on mass-produced main battle tanks.

The pattern observed in wheeled vehicles, however, may at first be somewhat puzzling, as some armored cars as far back as World War 1 appear to have comparable or even superior apparent power efficiencies than modern wheeled vehicles, including APCs. A few wheeled SPG designs developed after 1980 likewise show what appears to be abnormally high power efficiency. As discussed in the paragraph describing the preceding histogram, vehicles designed with a lower factor of safety for engine power output, whose operations are intended to be constrained to flat paved roads, are fully anticipated to demonstrate relatively high power efficiency on such roads. In fact, many of the armored cars and SPGs displaying abnormally high power efficiency were, in fact, derived from conventional civilian automobiles and cargo trucks, which were not intended for challenging cross-country maneuvers, and thus enjoyed very high power efficiency on roads, even though their overall mobility on rough terrain was quite poor.

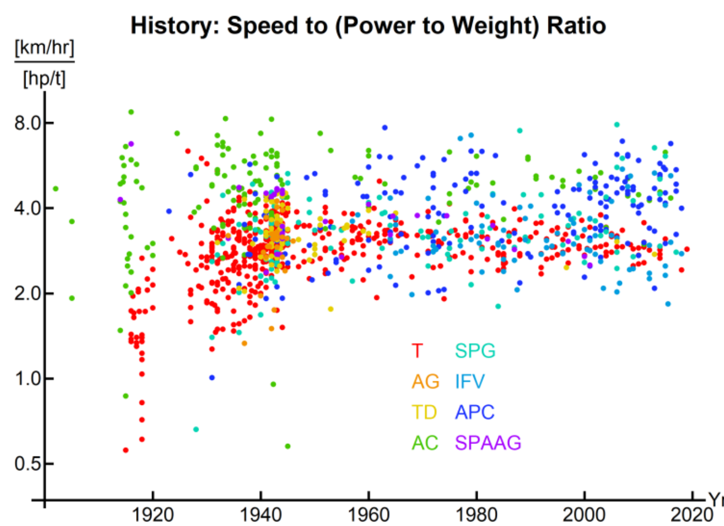


**Figure 54:** Historical evolution of the power efficiency of combat vehicles, in (kilometers per hour) per (horsepower per ton)

### 3.5. Vehicle Armament: Firepower

In the next several sections, we analyze the armament of ground combat vehicles. First, we present a brief analysis of key gun performance specifications in general, so these can be used in comparative vehicle analysis further on. We examined a set of 424 different guns and gathered data on a total of 772 projectiles used with these guns. The guns used in the analysis ranged from 4.37mm to 914mm in caliber, to examine if the same overall trends would be consistently observed for hand guns, aviation guns, field artillery, tank guns, naval guns, and railway guns. This analysis also includes data on low-velocity recoilless rifles and infantry mortars, for comparison.

The first analysis we conducted examined the relationship between the cube of gun caliber and projectile mass. We anticipated a linear relationship, since, on average, the relative proportions and overall shape of projectiles is consistent, from carbines to battleship guns. The resulting plot is presented in Figure 55, and is, in fact, quite linear, across 7 orders of magnitude of mass, from a bullet weighing just 1.6 grams to an 800mm railway gun shell weighing 7.1 tons. On average, the relative scaling ratio between projectile mass $M_{proj}$ and the gun caliber $c_{gun}$ was found to be:

$$M_{proj}\ [kg] = 1.45 * 10^{-5} * c_{gun}^3\ [mm^3]$$

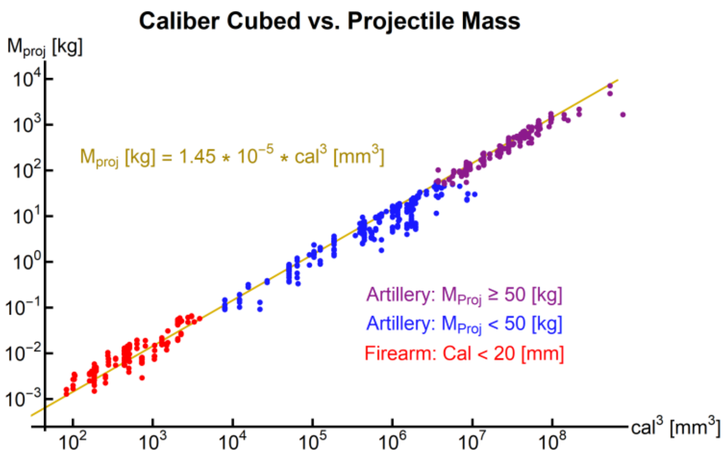


**Figure 55:** Relationship between the masses of projectiles, in kilograms, and the cube of their caliber, in cubic millimeters

Examination of the plot reveals that for firearms, there are many projectiles that lie above the line, and therefore, are relatively heavy, while for artillery firing projectiles below 50 kg in weight, many projectiles lie below the line, and therefore, are relatively light. This data for all projectiles is summarized in the histogram shown in Figure 57. The histogram shows the ratio of projectile mass, in kilograms to the cube of the gun caliber, in cubic millimeters, for all examined projectiles, with a single red line corresponding to the fit line from Figure 55.

It is easy to explain the observed effects: the overall fit line includes projectiles that are completely solid, as well as projectiles that have internal cavities filled with lightweight explosives, intended to detonate into shrapnel. It likewise includes short projectiles, such as pistol bullets and heavy rounds for conventional heavy artillery mortars, as well as long projectiles, like rifle bullets and armor-piercing naval shells. Thus, if we examine the three gun categories listed above:

- Most projectiles fired from firearms tend to be solid metal, since they do not have enough volume to carry a useful high explosive charge, and thus instead are optimized for penetration. This means that they have a higher overall average density, as compared to explosive artillery shells. The exception are solid but short bullets for pistols and submachine guns, which have less volume given the same starting caliber.
- Around 40% of light and medium artillery projectiles (up to 6 inches in caliber) are high explosive shells, produced with internal cavities for explosive filler. This means that they are typically lighter than the solid armor piercing rounds of the same caliber. Somewhat ironically, sub-caliber discarding sabot ammunition used by modern tanks, like APFSDS (Figure 56), also tends to be relatively light, since these rounds are intentionally much narrower than their parent gun bore, to increase muzzle velocity, sustained velocity in flight, and armor penetration. When fired, these sub-caliber penetrators are held in a lightweight full caliber sabot, discarded after leaving the barrel.
- Most projectiles for heavy and superheavy artillery do have high explosive filler as well, but typically as a smaller fraction of overall projectile weight, since these guns are generally intended for use against hardened targets, such as enemy fortifications built using thick reinforced concrete and steel, or strongly armored enemy battleships. Thus, most of the volume of these projectiles is steel, with a small high explosive charge close to the projectile base.

**Figure 56:** APFSDS Sub-Caliber Penetrator and its Sabot

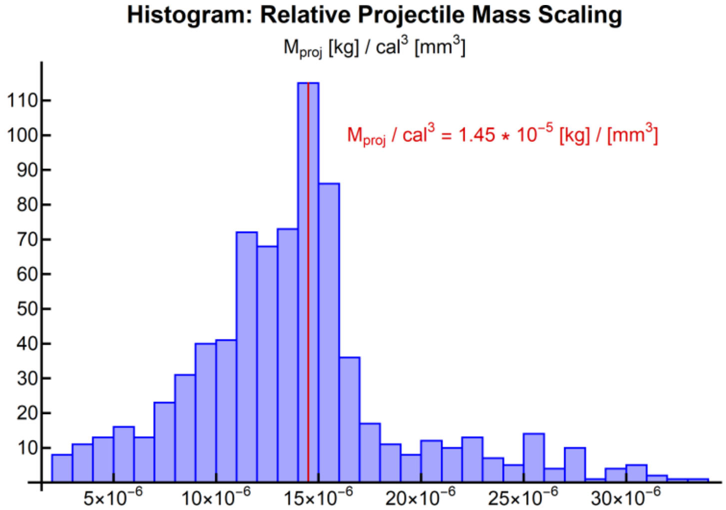


**Figure 57:** Histogram of the ratio of projectile mass, in kilograms, to the cube of the gun caliber, in cubic millimeters

The next analysis of projectiles and guns examined the relationship between the size of a gun and the corresponding kinetic energy of the projectile at the muzzle. We found that the best correlation happens to be between the total internal volume of the gun barrel $V_{brl}$ and the projectile muzzle energy $E_{muz}$ – which is linear in the maximum energy-to-volume limit. This trend is shown in Figure 58. On average, for the most energy-efficient guns, we found the relationship to be:

$$E_{muz}\ [J] = 0.128 * V_{brl}\ [mm^3]$$

This relationship is likewise consistent across 7 orders of magnitude, and takes into account the caliber of the gun, as well as the length of the gun when calculating the total internal barrel volume. This is important, because the longer the gun is, the more energy can be transferred to the projectile by the expanding powder gases before the projectile leaves the barrel and the gases dissipate, leading to higher muzzle velocity, and thus, higher muzzle energy.

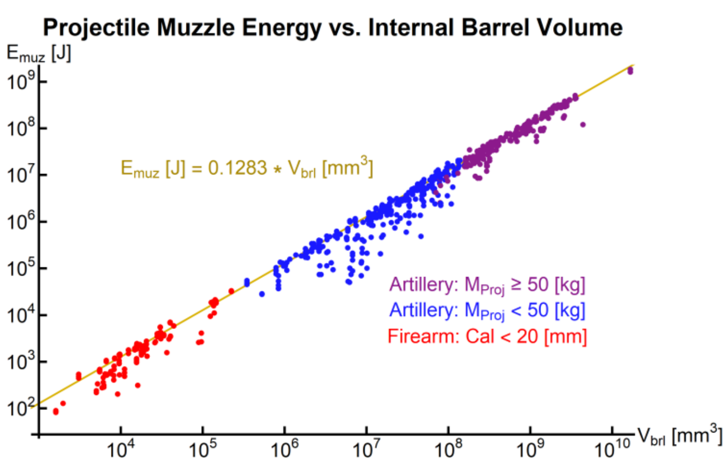


**Figure 58:** Relationship between projectile muzzle energy, in Joules, and internal gun barrel volume, in cubic millimeters

In this analysis, we again broke down the data into three domains, each with their own specialties. The overall histogram of energy efficiency is represented in Figure 59. As with the example for projectile mass, the histogram plots the characteristic ratio, in this case, muzzle energy to barrel volume, for all projectiles, with a single red line representing the fit line from Figure 58.

- It is evident that many firearms are somewhat below the energy-volume fit line, meaning that their ammunition is fired with lower muzzle energy than could theoretically be produced by a gun of the same size. This is likely because firearms are often designed for very long barrel life, on order of 10 000 rounds. The most significant factor determining barrel life is how energetic each shot is, both due to the material fatigue experienced by the gun barrel and chamber, as well as the barrel wear incurred with each successive shot. Thus, reducing the energy of the round helps increase barrel life. Another factor is safety: since firearms need to be as light as possible, they cannot be built out of excessively thick steel, like tank guns and naval artillery. Thus, reducing the relative energy of their ammunition reduces the risk of explosive destruction of the chamber.
- While many light and medium artillery pieces sit quite close to the best fit line, some guns in this range fall far below the best fit, almost by a full order of magnitude. These are primarily man-portable muzzle loaded infantry mortars, recoilless guns, low velocity howitzers, and conventional gun mortars optimized for high fire trajectories. All of these weapons fire ammunition with intentionally low muzzle velocity. In some cases, the purpose is to deliver plunging high explosive shells on nearby targets behind terrain obstacles, so short range is required (conventional gun mortars, howitzers, and infantry mortars). In other cases, the purpose is to reduce the resultant recoil and produce a lightweight weapon which fires large high explosive shells, but can be transported by team of foot soldiers or a light utility vehicle (infantry mortars and recoilless guns). Thus, these classes of guns exhibit much lower muzzle energies than conventional guns of the same caliber and barrel volume.
- Heavy and superheavy artillery generally falls close to the best fit line, since these guns are typically used at long ranges, and fire very heavy armor piercing ammunition, which relies on high muzzle velocity for effective armor penetration. Some guns in this range, however, are also used as heavy bombardment mortars optimized for plunging fire over defensive walls, so their relative muzzle energy is low by design.

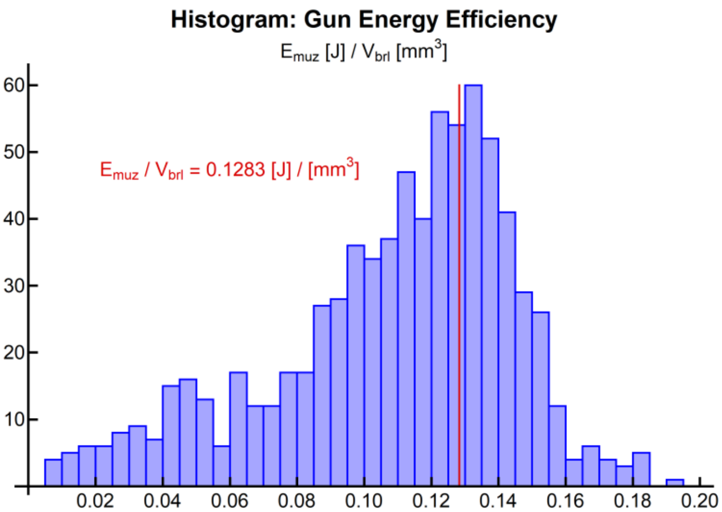


**Figure 59:** Histogram of the ratio of projectile muzzle energy, in Joules, to internal gun barrel volume, in cubic millimeters

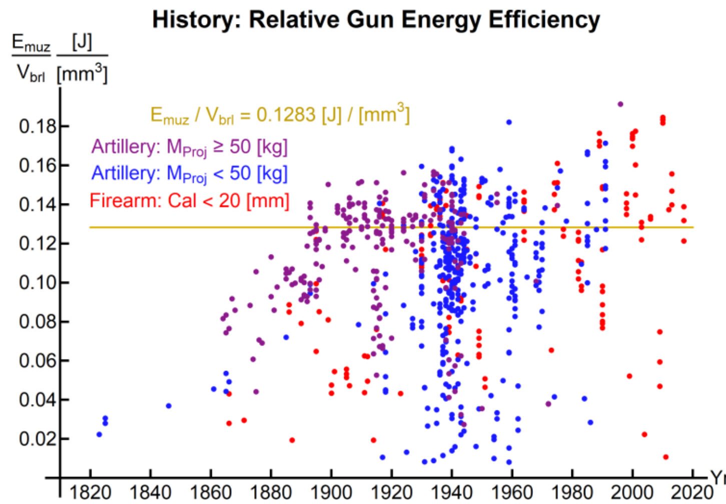


**Figure 60:** Historical evolution of the ratio of projectile muzzle kinetic energy, in Joules, to internal gun barrel volume, in cubic millimeters

The historical record of this energy efficiency is presented in Figure 60. As can be seen, there is a gradual, slow progression of the best possible energy efficiency factor that can be attained, with the current record, judging from available data, just under $0.2\ [J]/[mm^3]$. It is likely that guns used in the future will be able to reach even higher efficiency factors, but this will require several major developments:

- Stronger, more resilient materials will be necessary for gun chambers and barrels, to allow for higher chamber pressures to be safely reached over hundreds or thousands of shots, without risk of premature material fatigue fatally weakening the gun.
- Stronger, more resilient materials will be necessary as internal barrel liners, to reduce barrel wear with each shot, since this wear ultimately affects the shape of the barrel, and reduces the accuracy of the gun unless it is relined. This is particularly important for tank guns, since modern fire control systems allow tanks to accurately hit their targets within just one or two shots, so time wasted on an inaccurate shot may prove to be fatal to the tank and its crew.
- More energetic explosives will be necessary to fire projectiles at higher speeds without requiring impractically large gun chambers
- More aerodynamic projectiles will be necessary to reduce energy losses due to air resistance, which ultimately will negate gains in muzzle velocity since air resistance is significantly increased at high velocity

If better materials are developed, which do allow for much better energy efficiency, future combat vehicles could be armed with much more compact main guns. For tanks, this could allow to reduce the overall size of the turret, making the tank a more difficult target, while for IFVs and APCs, it could allow much more powerful armament to be carried without reducing the space available to hold infantry.

### 3.6. Vehicle Armament: Armor Penetration

Having examined the relationships between gun caliber, internal gun barrel volume, projectile mass, and projectile muzzle energy, we further examine armor penetration performance of commonly used projectile classes, and its relationship to gun and projectile specifications. In this part of the study, we examine several different types of projectiles historically used as armor piercing ammunition:

- Armor Piercing (AP): the simplest kind of armor piercing projectile, generally resembling a bullet with a hardened, pointed nose, with projectile diameter equal to the caliber of the gun. The earliest shells of this type were developed by British engineer Sir William Palliser for naval use in 1863.
- Armor Piercing Ballistic Capped (APBC): standard AP shell but with a thin sheet metal ballistic cap over the nose, improving shell aerodynamics by reducing drag, increasing the sustained velocity in flight over long range
- Armor Piercing Capped (APC): standard AP shell, but with a thick penetrating cap of relatively soft steel over the hardened nose, used to protect the underlying AP shell from fracturing when impacting face-hardened armor plate, and to reduce the risk of ricochet, thereby improving penetration. These shells were first developed by Russian vice admiral Stepan Makarov in 1893, likewise for naval use.
- Armor Piercing Capped Ballistic Capped (APCBC): APC shell, but with an additional ballistic cap, to reduce drag and increase sustained velocity
- Armor Piercing Composite Rigid (APCR): projectile with a very dense, hardened, pointed, sub-caliber core, often based on tungsten carbide, encased in an aerodynamic full-caliber jacket of a lower density metal, such as aluminium alloy, producing a shell

overall much lighter than a conventional AP round, allowing for higher muzzle velocity. Upon impact, the dense core penetrates the target armor plate, while the aluminium jacket is left outside. Judging from available data, the first use of APCR rounds in combat was in 1940, when the Germans introduced the PzGr.40 series of tungsten core ammunition for their 37mm, 50mm, and 75mm anti-tank guns.

- Amor Piercing Discarding Sabot (APDS): projectile with a similarly dense sub-caliber core, held in a lightweight sabot that breaks away shortly after leaving the barrel, allowing the sub-caliber core to proceed to target on its own, and thus experience less atmospheric drag and sustain higher velocity than an APCR round. The first APDS rounds were used by the British in 1944, as ammunition for their 6pdr and 17pdr anti-tank guns [54].
- Armor Piercing Fin Stabilized Discarding Sabot (APFSDS): similar to an APDS round, but using a long-rod sub-caliber core, which is stabilized with aerodynamic fins to maintain trajectory and prevent tumbling over long range. The first example of this ammunition to see widespread service was the 3BM3 115mm APFSDS round [55], developed for the T-62 medium tank, introduced in 1961.

When an armor piercing projectile hits an armor plate, some or all of its kinetic energy is absorbed through the deformation of the target plate, potentially leading to penetration. Whether or not there will be a penetration depends on the size and energy of the projectile and the thickness of the plate. Since a projectile will generally not produce a through hole larger than its own caliber, we can make the simple assumption that its kinetic energy is concentrated over its cross-sectional area during a penetration event, and that the maximum depth of penetration will be achieved when all of the kinetic energy is spent:

$$p \propto KE/A$$

Earlier, in Figure 58, we saw that the kinetic energy of a projectile at the muzzle is, generally speaking, proportional to the internal volume of the gun barrel. Thus, if we replace kinetic energy with barrel volume, we see that the penetration depth, to a simplified first approximation, ought to be generally proportional to the length of the gun barrel:

$$p \propto V/A = L$$

This dependence is explored in Figure 61, which shows a generally linear trend, as anticipated. The plot presents data on 229 different armor piercing projectiles, fired from 124 guns, primarily used during the Interwar Period, World War 2, and the early Cold War, prior to 1990. This data was likewise collected primarily from Wikipedia, where it was sourced from historical books, advertisement brochures made publicly available by manufacturers, as well as the website for the tabletop game Panzer War [56], which includes extensive analysis of armor penetration of World War 2 ammunition. Data from Panzer War was particularly useful, since the website authors normalized armor penetration data obtained from multiple nations to a single standard, since British, American, German, Russian, French, and Japanese standards for defining successful penetration differed during the War. Normalized data from Panzer War was provided under the definition of a successful penetration as one when there is a 50% probability of at least 50% of the mass of the penetrator passing through the target armor plate of a given thickness, assuming the Rolled Homogeneous Armor (RHA) plate is made of steel with a Brinell Hardness Number (BHN) of 270, and the projectile's incident angle was perpendicular to the plate surface, to avoid complications with accounting for sloped armor. Thus, where possible, Panzer War figures were used, instead of the original data tables.

The data gathered for each projectile included:

- The gun it was fired from, its caliber and length
- The projectile's name, category, weight, and muzzle velocity when fired with its designated charge
- Nominal penetration at ranges 100 meters to 3000 meters, as available

Once this data was collected, each projectile's list of range-dependent penetration values was fit to a simple quadratic function, to derive the expected penetration at point blank range against a perpendicular plate, thus estimating the projectile's maximum possible RHA penetration. This maximum predicted penetration was recorded and represented in the plots below.

The plot in Figure 61 shows the 7 categories of armor-piercing projectiles separated into 4 groups. Group 1 (G1) includes the AP and APBC projectiles, since the thin sheet metal aerodynamic ballistic cap would be irrelevant at point blank range, and would be expected to have a negligible effect on penetration. Group 2 (G2) includes APC and APCBC projectiles, since both of these categories carry the soft steel penetrating cap, designed to enhance performance of AP rounds. Group 3 (G3) includes APCR and APDS projectiles, since both of these use relatively short sub-caliber tungsten carbide penetrators. APFSDS rounds were kept in their own group, since considerably fewer different guns use this type of ammunition, and the term technically covers a large variety of customized penetrators, which differ greatly in material, geometry, and overall construction. Projectiles whose classification was not specified in the data tables were not included in any group, and are plotted in gray.

Each of the 3 groups of armor-piercing projectiles was fit to a separate trend line. G1 projectiles had an average maximum penetration of just under 30 mm of RHA for every 1 meter of barrel length:

$$P_{G1}\ [mm] = 0.0296 * L_{br}\ [mm]$$

The penetrating cap of G2 projectiles enhanced penetration by around 20% as compared to G1, on average, though there was some overlap in the overall ranges of G1 and G2. The standard sub-caliber tungsten core rounds were able to penetrate around 60% more RHA steel, as compared to G1. No line could be fit to APFSDS penetrators, which were almost always superior to all other types of rounds, due to the large diversity of APFSDS material choice and construction.

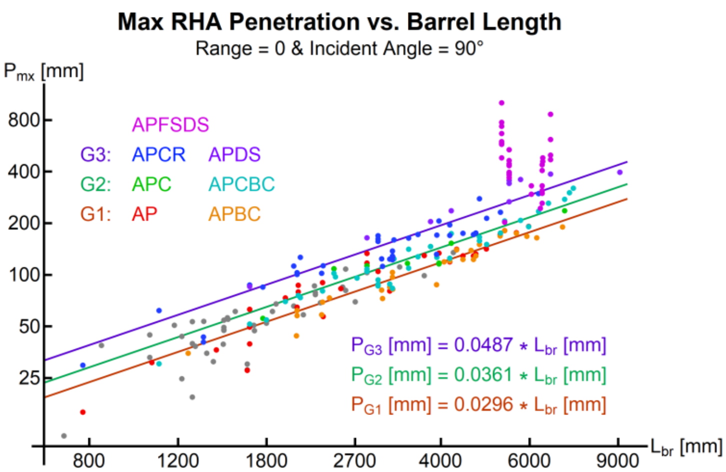


**Figure 61:** Relationship between gun barrel length, in millimeters, and RHA plate penetration at point blank range, in millimeters

The plot above was built under the assumption that armor-piercing projectiles are fired using the largest practical explosive charge, to maximize muzzle energy, and thus would obey the linear relationship between internal gun barrel volume and projectile muzzle energy shown in Figure 58. To verify this assumption, a second plot was produced, using the actual muzzle energy of projectiles, divided by the gun barrel cross-sectional area, shown in Figure 62. In this analysis, it was found that G1 projectiles penetrate around 0.25 mm of RHA for every Joule of muzzle energy per square mm of cross-sectional area:

$$P_{G1}\ [mm] = 0.251\ Ke_P\ /\ A_{br}$$

If we compare this to the analysis looking at barrel length, we get a ratio of 0.118 Joules of muzzle energy per cubic mm of barrel volume, very close to the 0.128 value shown in Figure 58. Reasons for this slight disparity include the small sample size available for penetration data, the use of alternative data sources on projectile performance, where specific details on muzzle velocity differed slightly from sources used earlier, and the inherent imperfection of data produced using methods of the 1940s, which likely went through several iterations of rounding and re-estimation by the time it was published in different historical books.

If we compare G1 projectiles to G3 projectiles, we see that the tungsten core penetrators once again provide around 60% better penetration, as compared to standard AP rounds, showing very good consistency between the two models of penetration, based on explicit muzzle energy and on barrel length. However, comparison of G1 and G2 projectiles yields a very different result: instead of enhancing penetration by 20% as before, penetrating caps only offer an improvement of around 4% here. This indicates that G2 projectiles in this data set had a ratio of 0.138 Joules per mm$^3$ of barrel volume. The difference of around 16% is most likely a statistical artifact of imperfect data records, which could be negated by adding more data, since there is no indication that APC and APCBC shells of the World War era were shot with a consistently larger powder charge than AP and APBC shells, judging from the information tables available for this study.

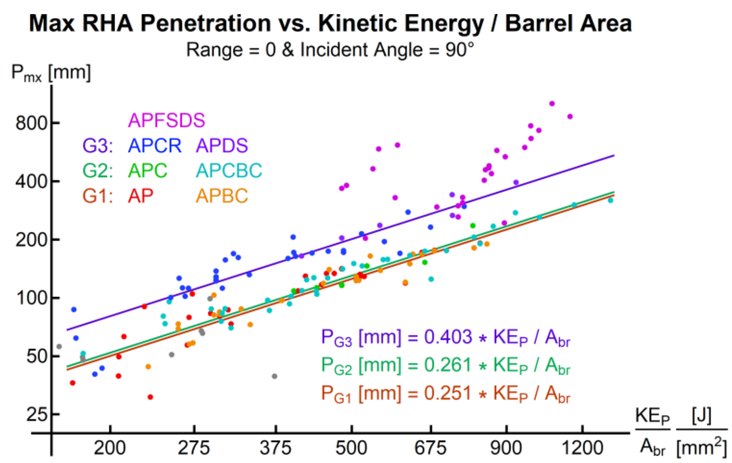


**Figure 62:** Relationship between the ratio of muzzle energy to the cross sectional area of the gun barrel, in Joules per square millimeter, and RHA plate penetration at point blank range, in millimeters

Having examined the dependence of armor penetration at point blank range on barrel length and projectile kinetic energy, we now examine the degradation in armor penetration with range, in Figure 63. These lines in this plot were produced by calculating a best-fit quadratic function of range-dependent penetration for each projectile in the database, and then dividing it by the magnitude of barrel length to normalize projectile performance. The averages of these normalized functions for each projectile category were then plotted as the representative line. Penetration degradation is displayed up to a range of 1.8 km, due to limited data on penetration beyond this range for some represented projectile categories.

The resulting plot shows that AP rounds have superior armor penetration to APBC rounds at short range, but are inferior beyond 600 meters. While it is possible this slight superiority of AP rounds at short range is a statistical artifact, it could potentially indicate that the thin aerodynamic ballistic cap on its own actually somewhat interferes with armor penetration, and thus provides a benefit only at longer ranges, since it allows the APBC projectile to sustain much higher velocity throughout its flight. The comparison between APC and APCBC shells shows only a small deviation in performance at long range. This could potentially be due to improper classification of some APCBC shells as APC shells, which was observed and corrected for certain Russian and American projectiles when data from multiple independent tables was compared, or due to the small sample size of specifically APC shells. Nevertheless, APCBC shells are shown to provide superior penetration at long range, which was expected. APCR shells show a very interesting curve, delivering outstanding armor penetration at short range, but rapidly dropping off, becoming inferior to all but the simplest AP shells by 1300 meters. This is also expected, since APCR shells are historically known to suffer from this issue: while weighing less than AP shells, they had the same cross-sectional area due to the lightweight external ballistic jacket, which meant they lost kinetic velocity to atmospheric drag more quickly. This range limitation was one of the key factors motivating the development of APDS shells. Finally, both APDS and APFSDS shells show superior armor penetration at all ranges, as anticipated from their design.

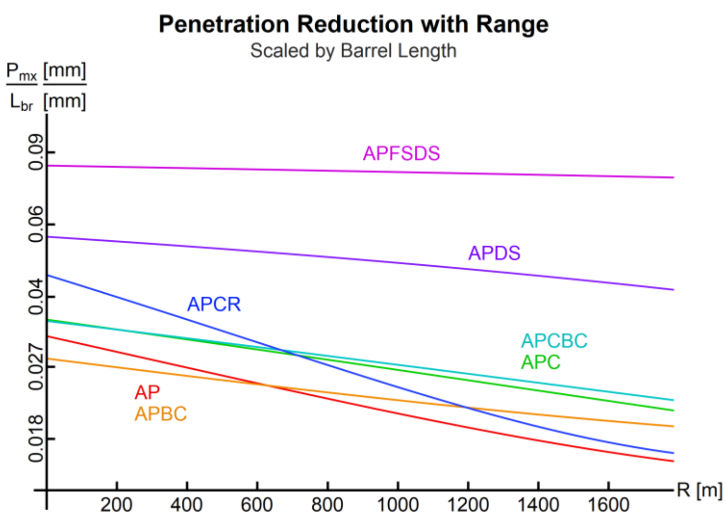


**Figure 63:** Average range-dependent reduction of RHA plate penetration for common types of armor piercing rounds

### 3.7. Vehicle Armament: Historical Analysis

Having analyzed the relationship between gun barrel caliber and projectile mass, the relationship between gun barrel volume and projectile kinetic energy, and the relationship between gun barrel length and point blank armor penetration, we can use the best fit coefficients to analyze firepower of our examined ground combat vehicles. Figure 65 shows the historical progression of the net mass of a single salvo from a combat vehicle: the combined mass of projectiles fired by each of the vehicle's guns once. We use data on a full single salvo here instead of just examining the main gun on its own to allow for fair representation of vehicles with multiple main guns, as well as to account for contributions of machine guns for vehicles not carrying large caliber primary armament. A good example of a relevant vehicle is the T-35 heavy tank, shown in Figure 64, which was equipped with 5 independent gun turrets, carrying a set of 1 × 76.2mm low-velocity gun, 2 × 45mm anti-tank guns, and no fewer than 6 × 7.62mm machine guns. No attempt was made in this study to account for the relative rates of fire of these weapons, since historical data on rates of fire was only available for a small subset of vehicle guns in the dataset, and it is well known that tank crews in actual combat consistently demonstrate sustained rates of fire lower than in training. Thus, we take the net mass of all projectiles assuming each weapon on the vehicle fires exactly once in a salvo. For vehicles with just one large caliber main gun supported by auxiliary machine guns, this is practically equivalent to analyzing the primary gun alone, since the weight of machine gun ammunition is insignificant compared to the weight of a full size artillery round.

**Figure 64:** T-35 Heavy Tank

The result agrees with our expectations, with the heaviest salvo masses observed for self-propelled guns, followed by tanks (primarily heavy tanks and MBTs), assault guns, and tank destroyers. The extreme SPG outliers are specialized superheavy artillery pieces, designed for siege operations, like the 600mm Morser Karl Gerat mortar shown in Figure 66. These were built in small numbers for the specific task of breaching thick reinforced concrete fortifications. At the low end of net salvo mass, below 1 kg, are IFVs, APCs, light armored cars, light tanks, and tankettes, which are all generally armed with guns under 40mm in caliber. This is an intentional design choice, especially for IFVs and APCs: since their primary purpose is the transport of infantry, they do not have space available for large guns or ammunition storage for such guns, and thus are built only with lighter weapons that do not detract from their primary mission, while providing sufficient firepower to deal with light enemy targets.

An important note needs to be mentioned about the appearance of straight horizontal lines in the data: only the best-fit coefficient for projectile mass, based on the cube of the gun caliber, as presented in Figure 55, was used here, since many of the vehicles in the main dataset had limited or no available data on their specific ammunition. Thus, vehicles armed with main guns of comparable or identical caliber will be presented as having identical projectile mass, and many calibers are common in international design, like 37mm, 76mm, 105mm, and 152mm.

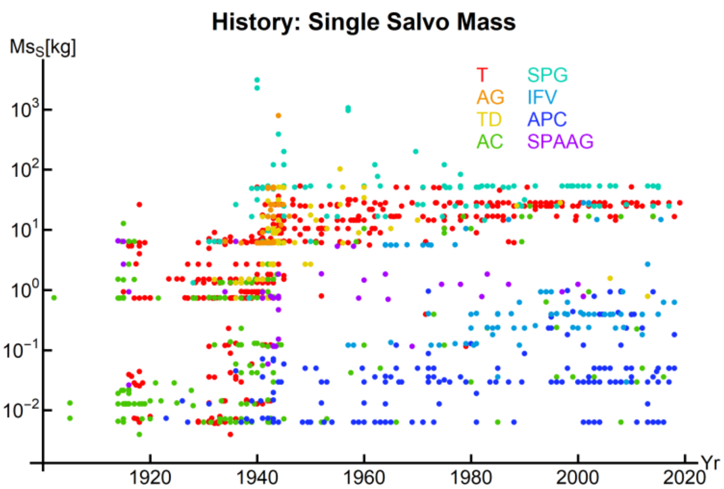


**Figure 65:** Historical evolution of the estimated total mass, in kilograms, of projectiles fired in a single salvo by all of the guns carried by a particular combat vehicle

**Figure 66:** Morser Karl Gerat 040 Superheavy Mortar

Figure 67 goes on to show the historical progression of the estimated muzzle energy of a single salvo, given the calibers and lengths of main and secondary guns used, multiplied by the coefficient shown in Figure 58. While the pattern is very similar to that observed in Figure 65, there are considerably fewer available data points, since a significant minority of the vehicles examined did not have reliable information regarding barrel length, unfortunately, and the barrel lengths of most machine guns were not recorded for this study. The presence of straight horizontal lines in this data is due to the fact that some specific guns were used on a large number of combat vehicles, so both the caliber and length of their primary armament were identical.

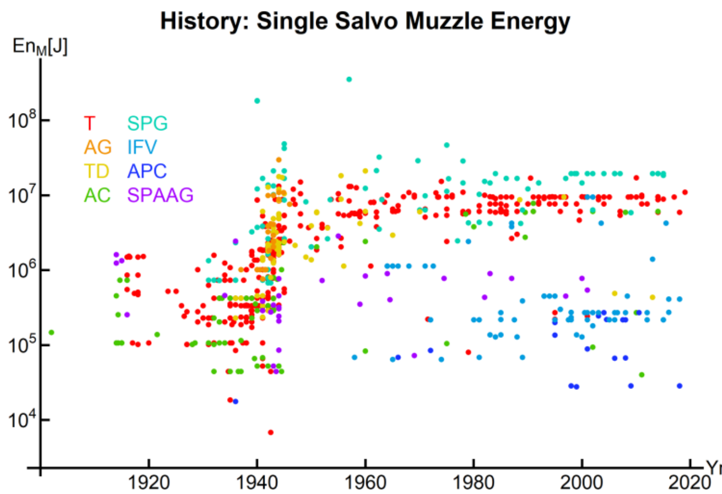


**Figure 67:** Historical evolution of the estimated total muzzle energy, in Joules, of projectiles fired in a single salvo by all of the guns carried by a particular combat vehicle

Next, we examine the historical progression of the ratio of salvo mass, in kilograms, to vehicle weight, in metric tons. In the resultant plot, shown in Figure 68, we see a stronger separation between tanks and SPGs. This follows logically from Figure 42 and Figure 65, as SPGs in service since World War 2 tend to be lighter in mass than contemporary tanks, while being armed with larger guns. While the observed SPG outliers are the aforementioned superheavy siege guns, the presence of TD outliers with unusually high ratios needs to be explained: these are the very light, paradroppable anti-tank vehicles, armed with large-caliber low-pressure or recoilless rifles, like the M50 Ontos from Figure 24.

It is interesting to note from this plot that the effective firepower-to-weight ratio of modern tanks seems to have been slightly decreasing since the 1970s, as the caliber of main tank guns has remained consistent (120mm for Western bloc nations, 125mm for Eastern bloc nations), while the vehicle mass has increased, due to continued growth in armor protection. However, this observed trend does not reflect improvements in modern armor-piercing ammunition, which offers superior armor penetration while allowing tanks to continue using the same gun model. Nevertheless, it would be reasonable to expect that larger guns will eventually be fitted to future tank designs, especially considering that America, France, Germany, and Russia have all been experimenting with larger caliber tank guns since the 1980s.

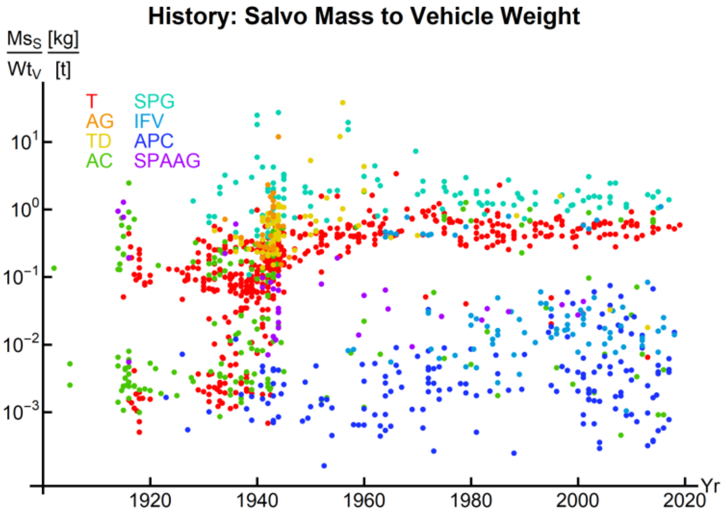


**Figure 68:** Historical evolution of the ratio between the total mass of projectiles fired in a single salvo, in kilograms, and the full weight of the combat vehicle, in metric tons

Figure 69 demonstrates the relationship between net salvo muzzle energy and vehicle weight, agnostic to the historical progression. In this view, the differences in firepower can be seen even clearer. Tanks generally appear to have around half an order of magnitude lower muzzle energy per unit weight than SPGs or high-performance TDs, while assault guns have very comparable muzzle energy per unit weight to tanks. Lightweight cannon-armed armored cars, surprisingly, are comparable to tanks on this parameter. The lowest coefficient of muzzle energy per unit weight belongs to IFVs and SPAAGs, since these are often heavy, relatively well armored vehicles, carrying low-caliber, fast-firing autocannon.

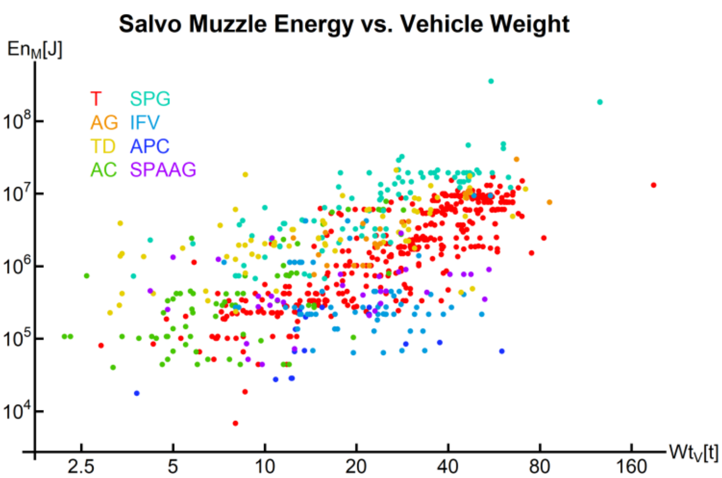


**Figure 69:** Relationship between the total muzzle energy of a single salvo, in Joules, and the full weight of the combat vehicle, in tons

Finally, we examine the predicted armor penetration of vehicles in the study, as it evolved over the past century. This plot was produced using the data fit for simple AP shells striking a perpendicular RHA plate at point blank range, based on gun barrel length, as presented in Figure 61. Use of superior armor piercing ammunition would proportionally shift the whole plot upwards. Certainly the most significant observation is the approximately 3 fold increase in armor penetration of tank guns in just 5 years of World War 2, between 1940 and 1945, showing that gun length grew rapidly. While the longest anti-tank guns used on tanks of the Interwar Period just barely exceeded 2 meters in barrel length, like the 45mm L/46 20K used on the T-35 heavy tank (Figure 64), the most powerful anti-tank guns used in combat during World War 2 were well over 6 meters in length, like the 128mm L/61 PAK-40 of the German tank destroyer Sturer Emil (Figure 70). Following the War, armor penetration of tanks appears to have remained steady and consistent, because instead of mounting increasingly longer main guns, tank engineers have instead focused on developing more effective APFSDS ammunition, as discussed in the section introducing armor penetration estimates.

**Figure 70:** Sturer Emil Tank Destroyer

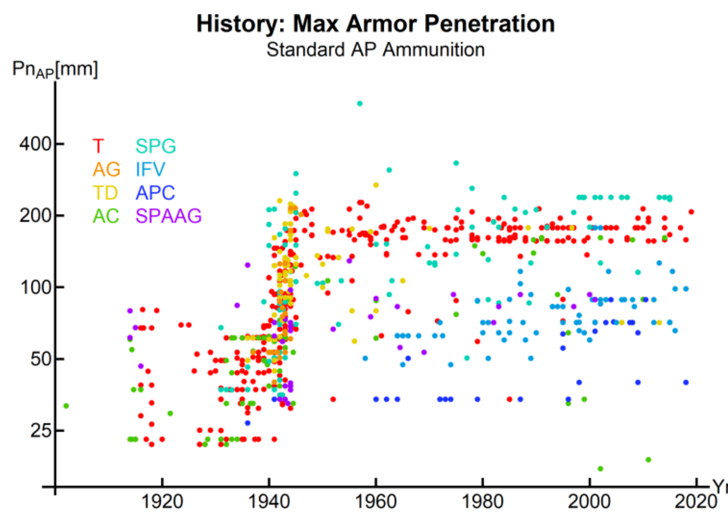


**Figure 71:** Historical evolution of the maximum armor penetration, in millimeters, of a combat vehicle firing standard AP rounds against a perpendicular RHA plate at point blank range

### *3.8. Vehicle Armor Protection*

Finally, we address the question of combat vehicle armor protection. Excellent data is available for many vehicles developed prior to 1970, since historians have conducted extensive research in declassified archives and in tank museums. Reliable, accurate, easily comparable data for newer vehicles, especially tanks, is somewhat more challenging to find, since many of these designs are still in active service around the world, and thus, major industrial nations have a major interest in not revealing their detailed armor specifications. Furthermore, in the late 1950s / early 1960s, tank armor ceased to be simple face-hardened steel alloy plates, as composite ceramic armor was introduced, on tanks like the American T95 medium tank (Figure 72) and the Russian T-64 main battle tank. Henceforth, tanks would be protected against enemy gunfire with complex sandwiches of steels, ceramics, and glasses. Furthermore, even soft materials like rubber were introduced, used as filler for spaced armor intended to defeat HEAT shaped charge rounds, used on armor packages like the British Stillbrew package (Figure 73), while lighter armored vehicles, such as IFVs and APCs, were now protected by aluminum alloy armor. For some of these vehicles, when data is available, only the net overall thickness of the composite armor package is provided, without breakdown of internal details, while others only have data on the equivalent RHA thickness that would offer the same level of protection as the specific tank's armor layout, with independent values for APFSDS and HEAT munitions.

**Figure 72:** T95 Medium Tank

**Figure 73:** FV4201 Chieftain Main Battle Tank with Stillbrew Crew Protection Package

Tank armor became even more complex when Explosive Reactive Armor (ERA) began to be used during the 1980s. The first successful ERA system to be used in combat was Blazer (Figure 74), integrated on Israeli tanks during the 1982 war in Lebanon. Since then, ERA blocks have become an obligatory element of Russian, Chinese, and other Eastern bloc tanks, though their use in the West has been quite limited. While early ERA blocks were only effective against HEAT munitions, new systems developed in Russia, made using thick steel sheets, are also effective at reducing APFSDS effectiveness. Also in the early 1980s, the first hardkill Active Protection Systems (APS) began to be used, starting with the Russian Drozd. These countermeasures are designed to deflect or destroy incoming munitions before they reach the tank, by shooting a counter-projectile into the path of an approaching round, further enhancing vehicle protection. Countermeasures like ERA and APS are, unfortunately, challenging to explicitly quantify in terms of "effective thickness" so they remain outside of the scope of this study.

**Figure 74:** Magach 5 (M48A5) with Blazer ERA

Armor thickness analysis for tanks produced since the 1960s presented in this section will rely on publicly available published data on effective RHA thickness of the primary composite armor packages only, as that metric still remains a useful basis of comparison. For vehicles with alternative armor materials, such as aluminium alloys, the actual physical thickness will be used: even though aluminium is a much weaker material than steel, it is not possible to calculate an effective RHA steel equivalent without having detailed information on the specific aluminium alloys and post-production treatments used in manufacturing.

The plot in Figure 75 shows the thickest armor protecting combat vehicles in this study. For tanks, armored cars, and many IFVs and SPGs, this is typically the armor protecting the front of the turret. For assault guns and tank destroyers, this is the armor at the front of the gun casemate. For APCs, SPAAGs, and some IFVs and SPGs, this is the armor at the front of the hull. These surfaces are always protected by thicker armor than the sides or the rear, as it is anticipated that in proper tactical deployment, enemies are most likely to shoot the front. Shots against the side or rear are most commonly expected when vehicles are ambushed or surrounded, which often means that they were poorly deployed and led. Also, the plot does not take into account the slope of the armor, only its nominal absolute thickness, which means that in battle, its effective line-of-sight thickness against rounds coming in on flat trajectories will always be higher, especially for vehicles with strongly sloped armor.

It can clearly be seen that the most effective armor by far is carried on modern main battle tanks, in some cases with equivalent stopping power in excess of 1 meter of RHA against kinetic penetrators, thanks to modern developments in materials science. It can also be seen that SPGs, IFVs, and APCs built in the past 60 years generally have armor no greater than 100mm in overall thickness, including light materials like aluminum, which makes up most of the thickness for many vehicles in these categories carrying more than 20 to 25 mm of armor. This level of protection is more than sufficient to stop incoming heavy machine gun and light autocannon ammunition, but wholly insufficient against contemporary tank rounds. Meanwhile, many of the light armored cars and APCs carry armor under 20mm in thickness, indicating they are only intended to survive machine gun ammunition, but nothing more serious, in accordance with their respective intended roles as fast scouts and "battlefield taxis" for the infantry.

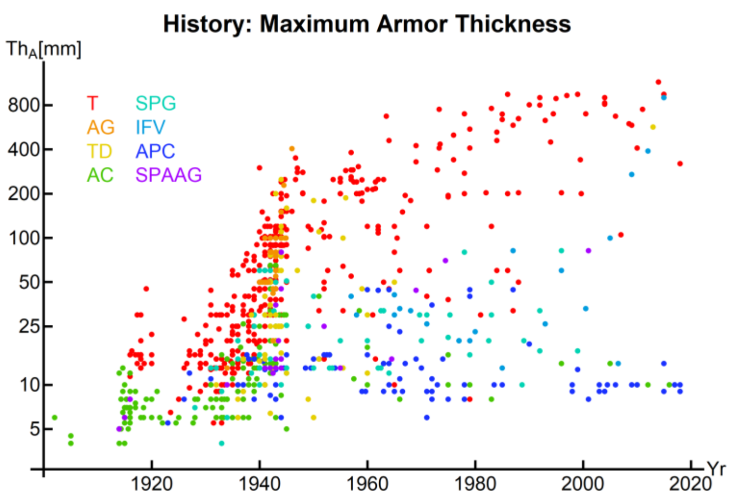


**Figure 75:** Historical evolution of the maximum armor thickness used on combat vehicles, in millimeters

Figure 76 shows the relationship between maximum armor thickness and overall vehicle weight. Unsurprisingly, the predominant trend is more or less linear, generally speaking, since, as we examined earlier, the range of overall vehicle dimensions is relatively narrow, and most combat vehicles are built with large, flat plates that are welded together, or out of smoothly curved cast parts, since those are the two most optimal pathways for manufacturing. Thus, due to the relatively simple, boxy shape common to almost all combat vehicles, and the size limitations imposed by transportation, it is reasonable to expect a generally linear overall trend.

The small cluster of vehicles lying well above the general trend, in the 40 to 60 ton range of vehicle weights, correspond to well-armored tanks and IFVs protected by complex composite armor packages. Their position on the graph serves as an excellent illustration of the remarkable weight efficiency of composite armor, as it allows for considerable levels of protection at much lower overall resultant vehicle weight.

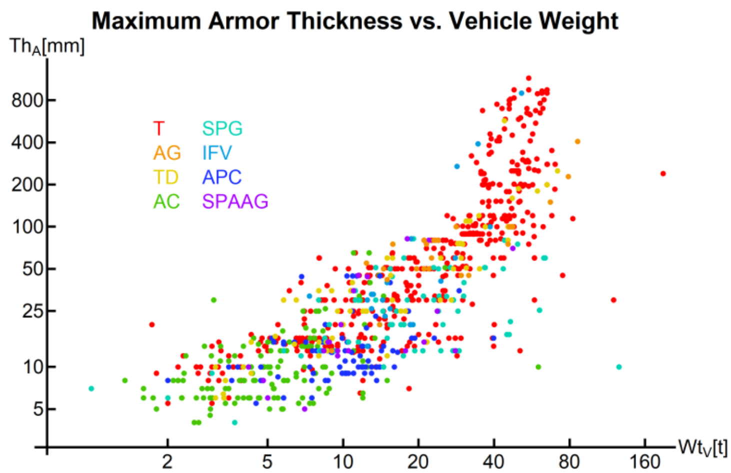


**Figure 76:** Relationship between the maximum armor thickness of a combat vehicle, in millimeters, and the vehicle weight, in tons

The final plots in this study present data comparing the maximum armor thickness used on combat vehicles and the estimated armor penetration of the most capable guns used on the same vehicles, assuming simple AP ammunition. It should be noted that the guns capable of the highest armor penetration may not necessarily be the largest-caliber guns mounted on a vehicle: in the example of the T-35 heavy tank (Figure 64), it is the secondary gun battery of long-barrel anti-tank guns that is capable of greatest armor penetration, since the primary gun was merely a short-barrel howitzer. The three interdependent plots examining the relationship between armor thickness and armor penetration include: a historical examination of the ratio of thickness to penetration (Figure 77), an analysis of thickness vs. penetration (Figure 78), and a logarithmic histogram of the ratio for the best represented vehicle categories (Figure 79). The analysis of thickness vs. penetration includes a gray line of slope 1, to give perspective to the estimated ratio.

While the presented comparisons do not take into account armor sloping, it actually balances out with the use of better armor-piercing ammunition quite conveniently. Using the armor penetration equation of Commandant Jacob de Marre for AP ammunition [57], we see that the equation accounts for the angle of impact using $(\cos\theta)^{1.4}$ where $\theta = 0°$ for a level impact against a perpendicular plate. Thus, armor plate that is sloped at 30° is 1.22 times more effective than perpendicular plate, similar to how capped APC and APCBC ammunition penetrates around 1.2 times more armor than simple AP ammunition at point blank range. Alternatively, armor plate that is sloped at 45° becomes 1.62 times more effective compared to perpendicular, similar to how tungsten core APCR and APDS ammunition is around 1.6 times more effective at penetrating armor plate. Thus, if we assume reasonable angles of slope, the use of armor piercing ammunition short of APFSDS, and reduced armor penetration at practical engagement ranges, it is reasonable to compare the absolute maximum thickness of armor with point blank penetration achieved by an AP round against perpendicular plate.

The new class of APFSDS ammunition began to proliferate in the 1960s, with the introduction of tanks with smoothbore guns such as the T-62 [55]. Prior to the 1960s, the majority of tanks had a Thickness-to-Penetration (T/P) ratio between 0.5 and 2. This observation can be explained by the general rule of thumb that many tanks were designed to be able to survive at least their own gunfire against the front of the hull or the front of the turret, since it can be reasonably assumed that the enemy will eventually design guns of equivalent power, if they don't already have some in service. In principle, following this guideline allows tanks to remain in service longer without needing to be continuously recalled for armor upgrades, or risk being easily lost in their first battle. After 1960, as APFSDS penetrators superseded older types of armor piercing rounds, the T/P ratio for main battle tanks rose significantly, reaching values as high as 6 in recent decades. This is a clear response to the growing capabilities of APFSDS ammunition, the best examples of which are likewise around 6 times more effective than simple AP ammunition fired from the same gun, as can be seen from Figure 61. Thus, we see that the same general guideline for tank armor protection is still largely observed in the design of modern MBTs.

The other well represented categories, tank destroyers, armored cars, and SPGs, all carry much lower levels of armor protection compared to their armor penetration capability, with only a few examples built with a T/P ratio as high as 1. For armored cars, this is expected, since they are predominantly intended for high-speed hit and run attacks, as well as scouting or minor infantry support missions, and are not the vehicles used in large-scale assaults against fortified enemy positions. For tank destroyers, this is likewise expected, since most of these vehicles are based on existing tanks, but are armed with considerably more powerful anti-tank guns, while maintaining the original tank's level of protection, or being upgraded to slightly thicker armor. Open top tank destroyers intended for long-range ambush attacks, like the Sturer Emil (Figure 70), have even lower T/P ratios because they were often built with armor capable of protecting them only from autocannon ammunition, while being armed with very powerful anti-tank guns.

Finally, SPGs are likewise expected to carry very low levels of armor protection for their armor penetration, since they are never intended to be directly in the line of fire. While the primary types of ammunition used by SPGs are high explosive and fragmentation rounds, all SPGs are also issued armor piercing rounds of several varieties, for use against enemy reinforced concrete fortifications. Depending on the gun, these can include a full range of APHE / APBCHE / APCHE / APCBCHE rounds, similar in design to regular armor-piercing rounds, but manufactured with an internal cavity filled with high explosive, which detonates the shell upon penetration for blast and fragmentation damage.

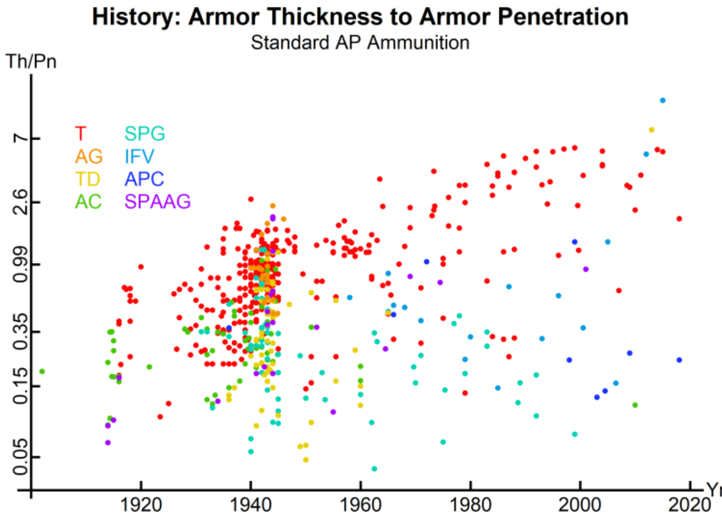


**Figure 77:** Historical evolution of the ratio between the maximum armor thickness used on a combat vehicle, in millimeters, and the maximum penetration the vehicle can achieve against an RHA plate using standard AP rounds, in millimeters

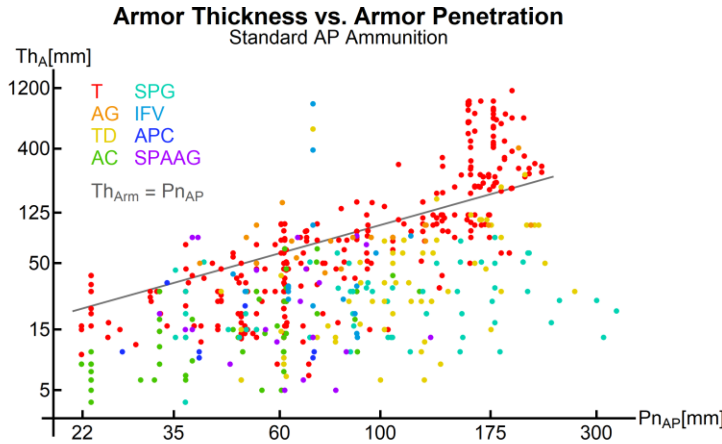


**Figure 78:** Relationship between the maximum armor thickness used on a combat vehicle, in millimeters, and the maximum penetration the vehicle can achieve against an RHA plate using standard AP rounds, in millimeters

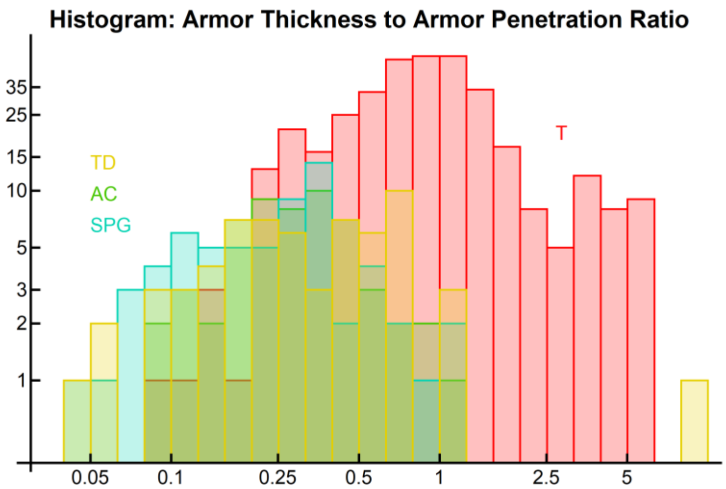


**Figure 79:** Histogram of the ratio between the maximum armor thickness used on a combat vehicle, in millimeters, and the maximum penetration it can achieve against an RHA plate using standard AP rounds, in millimeters, for selected vehicle classes

## 4. SUMMARY

In this study, we examined the history of armored fighting vehicles by tracking the evolution of their size, mobility, firepower, and armor protection. We saw how the intended combat role of different classes of armored vehicles was reflected in their design, and how an initial period of widespread experimentation during the Interwar Period and World War 2 helped engineers settle on basic guidelines and best practice design envelopes that have informed the world of combat vehicles since the 1960s. We also saw that while some technologies, for instance engines and armor protection, have continued to see extensive improvement in recent decades, other capabilities, for instance primary tank guns, have been somewhat stagnant. This is partly due to the international focus on developing improved ammunition for legacy guns, which is a much cheaper option than development of completely new guns, and partly due to the current relatively low threat of large-scale open warfare between modern main battle tanks, since the major developed nations of the world are generally averse to warfare with peer-level opponents, thankfully. Nevertheless, to ensure continued aversion to large-scale international warfare, it may be judicious to invest more effort to the development of more powerful guns, in anticipation of similar developments taking place around the world.

In addition to examining combat vehicle data in the context of historical progression, we examined major relationships between technical performance metrics, especially for mobility and for firepower. In doing so, we found potential areas for future technical improvement. For mobility, we identified that tracked vehicles, on average, require 50% more power per unit weight to be able to match the road speed of wheeled vehicles, judging from available data, likely due to the many energy losses associated with tracked locomotion. Development of better tracked systems, which could reduce internal energy losses and improve efficiency, could allow for improved fuel efficiency, and thus, practical range of future tracked combat vehicles. For firepower, we identified that there exists an overall limit to the muzzle energy practically achievable for a gun of fixed internal barrel volume. This is likely due to the materials that the gun chamber and barrel are made from, the maximum chamber pressure they can sustain, and their lifetime fatigue response. Development of tougher, more fatigue-resilient materials can allow the production of powerful yet compact guns, which would be critical for all categories of combat vehicles, but especially tanks and SPGs.

In summary, further research in these key areas would be of considerable benefit to the development of future armored fighting vehicles:

- Dynamically adjustable suspensions, which preemptively conform to terrain, to reduce vehicle vibration and enable higher sustained cross-country speeds
- More efficient drivetrains for tracked vehicles, to allow for higher driving speed without increasing the power to weight ratio (Figure 54)
- Stronger, more fatigue-resilient materials for gun chambers and barrels, to allow for higher projectile muzzle energy without increasing internal gun barrel volume (Figure 58)
    - This would in turn allow for higher armor penetration without increasing barrel length or developing superior armor piercing ammunition (Figure 61)
- Larger main guns for tanks and SPGs, with higher muzzle energy, to allow development of superior ammunition (Figure 67)
    - Not only would larger guns be able to use better armor-piercing rounds, but also heavier and more powerful general purpose high explosive shells (Figure 68)
- More versatile reactive armor and active protection systems, to reduce the need for excessively heavy primary armor packages (Figure 75)
- Lighter yet stronger ceramics and composites for more weight-efficient primary armor packages (Figure 76)
- More capable armor piercing ammunition, which could defeat an enemy tank's primary armor package even after encountering reactive armor or an active protection system (Figure 77)

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