Chapter 1

General Introduction

Considering the growth of the world population and its standard of living, the need for efficient methods for the synthesis of base chemicals is increasing. Therefore, the demand for clean reactions in industrial processes is intensifying. Transition-metal catalysed reactions can often be performed with high atom efficiencies, which is interesting from an environmental point of view.\(^1\) The rhodium-catalysed hydroformylation reaction of alkenes is a clean and mild, catalysed method for the synthesis of functionalised hydrocarbons on a large scale.\(^2\) In this reaction, aldehydes are produced by the addition of carbon monoxide and hydrogen to alkenes. A key issue of the hydroformylation reaction is the regioselectivity induced by the catalyst, since the linear product is often the desired product. In industry the aldehydes produced are converted to alcohols that are used as detergents (linear product) or plasticiser for PVC (branched product).

\[
\begin{align*}
R \text{--} & \quad + \text{CO/H}_2 \\
& \quad \rightarrow \\
& \quad R \text{--} \text{CH} = \text{CH}_2 \\
\end{align*}
\]

The hydroformylation reaction of alkenes was accidentally discovered by Roelen in 1938 while he was investigating the cobalt-catalysed Fischer-Tropsch reaction.\(^3\) Investigation of the reaction mechanism by Heck and Breslow showed that the active species in this (homogeneously) cobalt-catalysed reaction is HCo(CO)\(_4\), which is only stable under at least 100 atmosphere of carbon monoxide.\(^4\) High temperatures and pressures are necessary and the obtained selectivity for the linear aldehyde is low. In the sixties, the catalyst performance was improved by the introduction of tertiary alkylphosphines. Although the activity decreased using this phosphine modified catalyst, the stability of the catalyst and the selectivity for the linear aldehyde increased significantly, which made the catalyst applicable for industrial processes.
In the late sixties, Wilkinson discovered the hydroformylation activity of a rhodium-triphenylphosphine complex. This phosphine-modified rhodium catalyst operates under much lower pressure than the cobalt catalyst and shows a considerably higher selectivity for the linear aldehyde. Since the discovery of this rhodium-based catalyst, the ligand effects on the catalyst performance and the mechanistic aspects of the reaction have been extensively studied and have been reviewed many times.

### 1.1 Hydroformylation Reaction Mechanism

The commonly accepted, dissociative mechanism for the hydroformylation reaction proposed by Wilkinson is presented in Figure 1. The five-coordinate rhodium diphosphorus complexes drawn in this figure can be resting states of the catalyst, but rhodium complexes with one or three phosphorus ligands may also be involved. The reactive species in this mechanism are coordinatively unsaturated complexes formed by dissociation of a carbonyl or phosphorus ligand.

![Figure 1. Dissociative Hydroformylation Reaction Mechanism as Proposed by Wilkinson](image-url)
In general, the rhodium-hydride complex 1a is prepared in situ from a catalyst precursor. A free coordination site for alkene coordination is obtained in the CO dissociation step of the rhodium-hydride complex 1a (steps 1 and 2). In the hydride migration reaction either a linear or a branched rhodium-alkyl complex is formed (steps 3 and 3'). The rhodium-alkyl complexes can undergo β-hydride elimination that can lead to isomerised alkenes in case of the branched alkyl complex. The chemoselectivity of the reaction is determined by the difference in reactivity of the rhodium-alkyl complex towards CO insertion followed by hydrogenolysis (steps 5 and 6), β-hydride elimination (step 8, formation of isomers) and hydrogenation of the alkene or aldehyde. After the hydride migration (steps 3 and 3') and coordination of CO, insertion of CO occurs to give a rhodium-acyl complex (1g, step 4 and 5). At low temperatures and sufficiently high carbon monoxide pressure the insertion reaction is usually irreversible and thus the regioselectivity of the reaction is fixed in this reaction step. The preference for the hydride migration to form the linear and branched alkyl toward the β-hydride elimination are key steps in the determination of the regioselectivity. If a reaction step early in the reaction mechanism is irreversible, than this step determines the regioselectivity.

The unsaturated rhodium-acyl complex 1g undergoes either hydrogenolysis (step 6) or CO coordination (step 7). Hydrogenolysis completes the catalytic cycle with regeneration of the coordinatively unsaturated hydride complex 1b and production of either the linear or the branched aldehyde (step 6).

All the reaction steps proposed in the mechanism, except the hydrogenolysis, can be reversible under the ‘standard’ hydroformylation conditions, which results in a rather complicated kinetic expression for this reaction. Depending on the properties of the ligands used, different steps may control the reaction rate, which leads to simplification of the rate expression. Basically, two different types of simplified equations are proposed for the hydroformylation reaction. When the rate of the reaction is determined by the reactions early in the catalytic cycle (alkene coordination and hydride migration) the rate equation can be simplified as given below. This Type I kinetics is observed for most ligand modified rhodium catalysts.

\[
Rate \ (Type\ I) = \frac{A[Rh][alkene]}{B[CO] + C[alkene] + D[L]} \tag{I}
\]

When the rate of the reaction is determined late in the catalytic cycle (in the hydrogenolysis step) the rate equation can be simplified as given in equation II. Type II kinetics is often
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observed for electron-poor rhodium catalysts. The electron-poor character of the catalyst facilitates alkene coordination and hydride migration and the oxidative addition of hydrogen becomes rate determining.

\[
Rate \ (Type\ II) = \frac{E[Rh][H_2]}{F(CO) + G[H_2] + H[L]} \tag{II}
\]

Depending on the rate-determining step, different intermediates will be observed as resting states of the catalyst. In the case of the Type I kinetics the resting state of the catalyst will be the rhodium-hydride complex (1a), whereas in the case of Type II kinetics a rhodium-acyl complex (1b) will be observed as resting state of the catalyst.

1.2 Ligand Properties and Catalyst Structure

1.2.1 The Unmodified Rhodium Carbonyl Catalyst

Similar to the earlier developed, unmodified cobalt-catalyst, in the first commercially applied rhodium-catalysed hydroformylation process no additional phosphorus ligands were used. The active catalyst HRh(CO)₄ was prepared from rhodium carbonyl clusters ([Rh₄(CO)₁₂] or [Rh₆(CO)₁₆]). This rhodium catalyst is much more active than the cobalt catalyst, while the selectivity towards the linear aldehyde is also low.

Many detailed studies on the reaction kinetics and the resting state of the unmodified rhodium carbonyl catalyst using various substrates have been performed.⁸⁻¹¹ These studies showed that the rate-determining step of the hydroformylation reaction for this electron-poor rhodium catalyst is the hydrogenolysis (Type II kinetics). Garland and co-workers identified a rhodium-acyl intermediate as the resting state of the catalyst using in situ IR spectroscopy, which is consistent with the observed kinetics.¹²,¹³

1.2.2 Ligand Properties and their General Effect on the Catalyst Structure

Ligand properties have a large effect on catalyst activity and selectivity. Therefore many studies focussed on understanding the relation between the ligand properties, the geometry of the catalyst and the catalyst performance in the hydroformylation reaction.¹⁴⁻¹⁷ Tolman introduced the cone angle \( \theta \), which is an important steric property for monodentate ligands.¹⁸ The cone angle \( \theta \) is defined by the cone originating from a metal centre at 2.28 Å from the phosphorus atom, that encloses all the atoms of the substituents on the phosphorus atom (Figure 2). For ligands having large cone angles (\( \theta > 160^\circ \)), there is only space for one
ligand in the equatorial plane of a trigonal bipyramidal structure of the rhodium catalyst. These ligands form catalysts having the structure HRhL(CO)₃, which are very active hydroformylation catalysts. It must be taken into account, however, that the bulky substituents on the phosphorus atoms can mesh into one another to achieve higher coordination numbers than expected on the basis of the calculated cone angle (θ).

![Figure 2. Cone Angle θ and Bite Angle β](image)

An important steric property for bidentate ligands is the bite angle (β). The natural bite angle (βₚ) as defined by Casey and Whiteker is the preferred P-M-P chelate angle determined by the ligand backbone constrains only (Figure 2). The metal valence angles are not considered in the calculation of this angle. The bite angle has a large influence on the coordination mode of a bidentate ligand to the metal atom. Ligands having large bite angles (βₚ ≥ 100 °) coordinate preferably at the equatorial positions of the trigonal bipyramid (the ee coordination mode), whereas ligands having bite angles around 90 ° prefer coordination of one of the phosphorus atoms at an equatorial and the other phosphorus atom at an apical position (the ea coordination mode). Fast isomerisation between the ee and ea coordination mode can occur as has been observed in many studies involving of the catalyst structure.

![ee isomer](image) ![ea isomer](image)

Casey investigated the effect of the bite angle on the selectivity of the hydroformylation catalyst and he found a correlation between the regioselectivity and the coordination mode of the bidentate ligand in the trigonal bipyramidal structure. Studies of van Leeuwen et al. showed that the coordination mode of a bidentate ligand per se does not
determine the regioselectivity, as both isomers (ee and ea) may form the same four-coordinate intermediate in the hydroformylation cycle.\textsuperscript{17}

Tolman introduced the $\chi$-value to classify ligands with respect to the electronic ligand properties.\textsuperscript{22} The $\chi$-value is defined as the shift of the IR frequency (in wavenumbers) of the symmetric CO stretch of the Ni(CO)$_3$(ligand) complex compared to the reference complex Ni(CO)$_3$(P(t-Bu)$_3$. Many studies have been directed to the determination of the $\chi$-value of phosphorus ligands and the correlation of this ligand property to the activity and selectivity of the corresponding hydroformylation catalyst.\textsuperscript{19, 23} Electron-withdrawing phosphorus ligands show an increase of the reaction rate as a result of the facile carbon monoxide dissociation and stronger alkene coordination. Studies by Moser\textsuperscript{24} and van Leeuwen et al.\textsuperscript{17} showed, that introduction of electron-withdrawing groups on the phosphorus ligands, independent of the bite angle effect, can lead to active and selective catalysts.

Although large $\theta$-values and $\chi$-values can lead to highly active or selective catalyst performance, the electron-withdrawing character and bulkiness of the ligand cannot be increased infinitely. When the electron withdrawing capacity of the ligand is too high or the ligands are too bulky, the catalyst structure will change tremendously. Because of the high $\chi$-value or large $\theta$-value of the ligand, coordination of only one phosphorus ligand is favoured (formation of HRhL(CO)$_3$ instead of HRhL$_2$(CO)$_2$).\textsuperscript{7s, 19} This will have a negative effect on the selectivity of the reaction. Casey and van Leeuwen concluded that increasing the bite angle results in an increase of the ee:ea ratio together with an increase of the linear to branched ratios, but there is no smooth relationship. Also, above a certain value this bite angle effect levels off.\textsuperscript{26}

1.2.3 Phosphine Ligands in the Hydroformylation Reaction

In general, phosphine ligands are electron-donating ligands. The coordination of electron-donating phosphorus ligands to the electron-rich rhodium centre will have an effect on the affinity for coordination of the hydroformylation reactants. The electron-donating phosphorus ligands will lead to an increase in back-donation to the carbonyl ligands, hereby strengthening the metal-carbonyl bond. Alkene coordination will be disfavoured because of the high electron density on the rhodium centre. Therefore, the rate of the hydroformylation reaction will decrease with increasing electron-donating character of the phosphorus ligand and the alkene coordination will become the rate-determining step (Type I kinetics).

The steric properties of phosphine ligands are strongly depending on the substituents used. Alkylphosphines often have large cone angles because of the bulky alkyl substituents.
For example tri(tert-Butyl)phosphine has a cone angle of 170 °.\textsuperscript{19} The arylphosphines often have smaller cone angles than the alkylphosphines, but they introduce large steric hindrance close to the rhodium centre compared to phosphites for example. Although the monodentate ligands have rather large cone angles the obtained selectivity for the linear aldehyde is often moderate. Bidentate phosphine ligands, especially those with bite angles around 110 ° form very selective hydroformylation catalysts.

![Triphenylphosphine](image)

![Tri(tert-Butyl)phosphine](image)

Triphenylphosphine is probably the most extensively studied ligand for the hydroformylation reaction.\textsuperscript{5, 25 - 27} In the presence of carbon monoxide, the catalyst precursor HRh(PPh\textsubscript{3})\textsubscript{2}CO exchanges a phosphine ligand easily for a carbonyl ligand to form the rhodium-hydride complex HRh(PPh\textsubscript{3})\textsubscript{2}(CO)\textsubscript{2}, one of the intermediates of the catalytic cycle. Cavalieri d' Oro and co-workers investigated the reaction kinetics of the triphenylphosphine-modified catalyst.\textsuperscript{27} This study showed that the rate equation for this system depends on the substrate and phosphine concentrations. The reaction showed a zeroth order dependency on both CO and H\textsubscript{2} concentration (Type I kinetics). The selectivity for the linear aldehyde depends dramatically on the ratio between CO and ligand concentrations. Wilkinson\textsuperscript{5c} and Brown\textsuperscript{25} and co-workers examined the coordination chemistry of several rhodium-phosphine complexes that are potential intermediates in the hydroformylation reaction using IR and NMR spectroscopy. Under the conditions studied, HRh(PPh\textsubscript{3})\textsubscript{2}(CO)\textsubscript{2} was present as the most abundant species during the hydroformylation reaction as detected by \textit{in situ} IR and NMR techniques.\textsuperscript{26, 28} Moser investigated the hydroformylation reaction intermediates formed from a range of \textit{para}-substituted triphenylphosphine ligands.\textsuperscript{24} From their data they concluded that by decreasing the electron density on rhodium, the rate-limiting step shifts from “just after the formation of HRhL\textsubscript{2}(CO)\textsubscript{2} (L=PPh\textsubscript{3}) to just after formation of RhR(CO)\textsubscript{2}L\textsubscript{2} (L = (p-ClC\textsubscript{6}H\textsubscript{4})\textsubscript{3}P or L = (p-CF\textsubscript{3}C\textsubscript{6}H\textsubscript{4})\textsubscript{3}P).”

Several examples of bidentate phosphine ligands that have been applied in the hydroformylation reaction are depicted in Figure 3. Many studies have been performed aiming at finding a correlation between the bite angle of the ligand and the selectivity for the
linear aldehyde.\textsuperscript{16, 17} Investigation of hydroformylation catalysts based on the small bite angle ligands DPPE, DPPP and DPPB showed low selectivity for the linear product.\textsuperscript{29} Additionally, investigation of the catalyst structure showed high preference to form dimeric rhodium complexes.\textsuperscript{30}

Wide bite angle ligands have high preference for the \textit{ee} coordination mode as was shown by Casey and Witheker.\textsuperscript{21} They studied the catalyst structure formed under hydroformylation conditions using BISBI (Figure 3). The phosphorus atoms in the rhodium-hydride complex HRh(BISBI)(CO)\textsubscript{2} are both coordinated in the equatorial plane.\textsuperscript{21} Because the selectivity for the linear aldehyde using BISBI is high, it was concluded that this bis-equatorial coordination mode lead to high linear-to-branched ratios. Introduction of electron-withdrawing substituents on the aryl rings of the BISBI ligand led to a further increase of the selectivity for the linear aldehyde as well as the rate of the reaction.\textsuperscript{31} To study the exact nature of the electronic effect on the diphosphine-based rhodium catalyst, van Leeuwen et al. investigated a series of bidentate phosphorus ligands that are based on a xanthene backbone.\textsuperscript{17} The ligands used in this study have similar bite angles but the ligand basicity varies. This investigation showed that the linear-to-branched ratio increased with increasing $\chi$-value, but the selectivity of the reaction remained the same because the percentage of formed isomerised alkenes increased as well.

![Figure 3. Several Bidentate Phosphine Ligands and their Natural Bite Angles for Rhodium](image)

### 1.2.4 Phosphite Ligands in the Hydroformylation Reaction

Phosphite ligands have great potential in the hydroformylation reaction because of their electron-withdrawing character. Coordination of electron-withdrawing ligands result in strong $\pi$-back bonding from the rhodium centre. This will weaken the metal-carbonyl bond and strengthen the metal-alkene bond. The CO dissociation and alkene coordination are often fast compared to phosphine containing rhodium catalysts, especially in the case of
monodentate phosphite ligands, and the hydrogenolysis step becomes the rate-determining step (Type II kinetics).\(^{32}\)

Phosphite ligands introduce less steric hindrance close to the rhodium centre, because of the lower degree of substitution of oxygen compared to carbon. Therefore bulky substituents are introduced in most cases to increase the cone angle of these ligands. Although the large substituents on the phosphorus atom indeed increase the bulkiness of the ligand, often moderate linear to branched ratios are observed, together with high percentages of isomerised alkene. Another disadvantage of phosphite ligands is their sensitivity towards hydrolysis and alcoholysis, which makes them less suitable for industrial application.

![Tris(2-tert-Butyl-phenyl)phosphite](image1.png)  \(\theta = 170^\circ\)

![Tris(2,5-dimethyl-phenyl)phosphite](image2.png)  \(\theta = 190^\circ\)

Many research projects have been directed towards the influence of the ligand properties on the catalyst structure, the hydroformylation mechanism and the intermediates present during the reaction. Van Leeuwen et al. investigated hydroformylation catalysts containing bulky monodentate phosphite ligands.\(^{7c,19}\) Under hydroformylation reaction conditions the bulky monodentate phosphite ligands form rhodium-hydride complexes of the structure \(\text{HRhL(CO)}_3\). There is space for one ligand only because of the large cone angle of the ligands. The relative small hindrance close to the rhodium centre is probably causing low selectivity towards the linear aldehyde. Kinetic studies of the hydroformylation reaction catalysed by this bulky phosphite-based rhodium catalyst, revealed a zero order in alkene concentration and an approximate first order rate dependency on the hydrogen concentration, indicating that the rate-determining step is the hydrogenolysis.\(^{32}\) In situ IR studies confirmed this hypothesis by showing that the rhodium-acyl complex is present as the resting state of the catalyst during the hydroformylation reaction under these conditions.\(^{33}\)

Changing from monodentate phosphite ligands to bidentate ligands increases in several cases the selectivity for the linear aldehyde and results in a decrease in activity.\(^{34,35}\) The highest selectivities are observed for ligands containing a (substituted) bisphenol
backbone. Examples of bidentate phosphite ligands that have been used in the hydroformylation reaction are depicted in Figure 4. Similar to the diphosphine ligands the structure of the catalyst formed under hydroformylation reaction conditions and its influence on the catalyst performance has been extensively studied.

![Figure 4. Examples of Bulky Phosphite Ligands used in the Hydroformylation Reaction](image)

1.2.5 Phosphorus Amide and Amidite Ligands in the Hydroformylation Reaction

A relatively new group of ligands for the hydroformylation reaction are the phosphorus amide and phosphorus amidite ligands. Basically, these ligands contain one or more nitrogen substituents at the phosphorus atom. The nitrogen substituent has a large effect on the electronic properties of the phosphorus atom. Dialkylamino substituents on the phosphorus atom provide electron-donating phosphorus ligands, whereas for example pyrrolyl substituents on the phosphorus atom results in π-acidic phosphorus ligand.\(^{36, 37}\) Thus, the introduction of nitrogen substituents can provide a variety of electronic ligand properties. Depending on the substituents chosen, ligands are formed that have electronic properties compared to either phosphines or phosphites. Often the electronic properties of these ligands are in between those of phosphine and phosphite ligands. Because of the higher degree of substitution of nitrogen compared to oxygen, the phosphorus amide and amidite ligands create more steric bulk close to the phosphorus atom compared to phosphites.

Several phosphorus diamide and amidite ligands have been applied in transition-metal catalysed reactions.\(^{38-47}\) Some phosphorus amide and amidite ligands, depicted in Figure 5, have been used in the rhodium-catalysed hydroformylation.\(^{39, 40}\) Because this type of ligands is relatively new in the hydroformylation reaction only few studies have been performed concerning the catalyst structure formed under hydroformylation reaction conditions.\(^{40}\) No studies on the reaction kinetics and the structure of the intermediates present during the reaction have been published until now.


1.3 Catalyst Characterisation Studies

Many studies have focussed on the relation between the catalyst structure and its performance in the hydroformylation reaction and have shown that the chemo- and regioselectivity of the reaction is influenced by the geometry of the catalyst. In recent decades many (high-pressure) techniques have been developed or adapted to study the catalyst structure.

Most catalyst-characterisation studies focus on the geometry of the rhodium-hydride complex 1a as depicted in Figure 1. The rhodium-hydride complex is studied in the absence of substrate using (high-pressure) spectroscopic techniques. The number of phosphorus ligands that coordinates to the rhodium centre and the coordination mode are related directly to the catalyst performance. Investigating the structure of the rhodium-hydride complex gives a general idea about the effects of the ligand properties on the catalyst structure and results in most cases in plausible conclusions about the relation between the catalyst structure and its performance.

Another method for the investigation of the catalyst structure is the in situ characterisation of the intermediates present during the reaction. The hydroformylation reaction has been monitored using high-pressure spectroscopic techniques. This method gives a realistic idea about the relation of the structure of the intermediates and the activity and selectivity observed. It should be noted, however, that this method is sensitive toward the time scale of the spectroscopic technique used and its detection limits. In most cases, the complexes observed are resting states of the catalyst or catalyst decomposition products. Intermediates present in low concentrations are often not observed.

A third approach to study the structure of hydroformylation reaction intermediates is the use of model compounds. The rhodium metal can be replaced by iridium because of the
similar coordination behaviour. The reactivity of the iridium catalyst is lower than that of the rhodium catalyst, which can circumvent the problem of the difference in time scale of the reaction and the spectroscopic technique. Another possibility is the combination of the ligand and substrate function, which may lead to the isolation of stabilised intermediates.

Many different techniques have been developed to characterise the structure of complexes in solution. Every spectroscopic technique used for the characterisation of reaction intermediates has its advantages and disadvantages. Therefore combination of the various spectroscopic data obtained is necessary to characterise the catalyst structure completely. Two generally applied techniques for the characterisation of hydroformylation reaction intermediates are NMR and IR spectroscopy. These two techniques and their characteristic data described in literature are discussed in detail.

1.3.1 High-Pressure NMR Spectroscopy

NMR is a powerful technique for the characterisation of the hydroformylation reaction intermediates. Combination of the NMR data of the various nuclei ($^1$H, $^{13}$C, $^{31}$P and $^{103}$Rh) can lead to full characterisation of the complex structure. Although this technique gives a lot of information of the complex structure, it has two general drawbacks. First, the concentration range necessary for reasonable signal to noise ratios (10-100 mM) is well above the concentration region used for catalysis experiments (<1 mM). Metal-ligand equilibria may shift considerably upon concentrating the solutions, which hampers a direct comparison of the data observed in catalysis and in the NMR experiments. Second, standard NMR tubes are not suitable for in situ studies. The hydroformylation reaction is fast because of the high catalyst concentration needed. Gas diffusion and mass transfer become rate limiting because the reaction mixture is not stirred; complexes different from catalyst intermediates are observed (dimer formation).

Generally, the intermediates present during the reaction are only stable under syn-gas pressure. Therefore, special thick-walled (sapphire) NMR tubes and NMR probes have been developed that allow the study of complexes under high pressures and high temperatures. These tubes are very useful for the characterisation of the rhodium-hydride complexes in absence of substrate. To circumvent the mass transfer and diffusion limitation problems for in situ NMR experiments, high-pressure flow cells have been developed. The advantages of an high-pressure flow cell is the continuous supply of reactants and the optimal mixing of the reactants.
The position and multiplicity of the resonances and the coupling constants observed in the NMR spectra are characteristic of the structure of the complexes. The position of the hydride resonance in the $^1$H NMR spectrum varies between (-8) – (-12) ppm depending on the electronic properties of the other ligands coordinated to the rhodium atom.\textsuperscript{17, 48} The $^1$$_{\text{RhH}}$ coupling constant observed for the ee isomer is usually approximately 3 Hz, for the ea isomer this value is larger.\textsuperscript{66, 67} The $^2$$_{\text{HPH}}$ coupling constant is informative of the coordination mode of the phosphorus ligands or the degree of distortion of the trigonal bipyramidal structure. Large $^2$$_{\text{P_H}}$ coupling constants of approximately 100 Hz are characteristic of a trans phosphine-hydride coordination mode, the trans phosphite-hydride coordination mode can give $^2$$_{\text{P_H}}$ coupling constants upto 180 Hz.\textsuperscript{54-57, 66, 67} Small $^2$$_{\text{P_H}}$ coupling constant ($\approx$ 3 Hz) are observed for a cis phosphorus-hydride coordination mode.\textsuperscript{65} If there is fast exchange of the phosphorus ligands between the equatorial and apical positions an averaged resonance and coupling constant are observed for the equilibrium mixture of the ee and ea coordinated complex.\textsuperscript{17, 58} Coordination of the phosphorus ligands in the equatorial plane of a slightly distorted trigonal bipyramid also leads to an increase of the $^2$$_{\text{P_H}}$ coupling constant (10 - 20 Hz).\textsuperscript{48}

The phosphorus chemical shift depends on the substituents at the phosphorus atom and in the case of bidentate ligands the P-Rh-P chelate ring formed.\textsuperscript{59} Generally aryl phosphine ligands coordinated at a trigonal bipyramidal rhodium centre have chemical shifts of approximately 20 - 40 ppm. The value of the $^1$$_{\text{RP}}$ coupling constant is around 120 -150 Hz.\textsuperscript{17, 25, 60, 63} Aryl phosphite ligands coordinated at a trigonal bipyramidal rhodium centre have chemical shifts of approximately 150 - 170 ppm. The $^1$$_{\text{RP}}$ coupling constant is larger than that of comparable phosphine ligands (± 240 Hz).\textsuperscript{17, 48, 64} The chemical shifts and $^1$$_{\text{RP}}$ coupling constants observed for phosphinites, phosphorus amides and phosphorus amidites are strongly depending on the $\pi$- acidity of the ligand.\textsuperscript{39, 40}

Only few NMR data of carbonyl ligands have been published. The chemical shift of the carbonyl ligands is approximately 195 - 180 ppm.\textsuperscript{25, 48} In many cases the equatorial and apical carbonyl ligands are in fast exchange and averaged resonances and coupling constants are observed.\textsuperscript{25, 48} The $^1$$_{\text{RRC}}$ coupling constant varies between 50 - 70 Hz, the $^2$$_{\text{PC}}$ coupling constant varies between 3 Hz (cis relation) and 50 Hz (trans relation).\textsuperscript{25, 48} Rhodium-acyl carbon atoms are found at lower field in the $^{13}$C NMR spectrum. The chemical shifts observed for these carbon atoms are around 240 – 230 ppm.\textsuperscript{25, 62}

$^{103}$Rh NMR is used in few cases to investigate the structure of the rhodium complexes formed under catalysis conditions.\textsuperscript{63} The NMR sensitivity of the rhodium nucleus is low because of the small gyromagnetic ratio of the rhodium nucleus and therefore long collection
times are prerequisite when a direct measuring method is used. Using an inverse detected HMQC sequence (two dimensional X, $^{103}$Rh NMR using X = $^1$H or $^{31}$P) leads to a theoretical sensitivity enhancement of 5630 for X = $^1$H or 360 for X = $^{31}$P. Very little data have been published for hydroformylation reaction intermediates.\textsuperscript{63} Chemical shifts between $-$785 ppm and $-$1073 ppm have been measured for rhodium-hydride complexes containing bidentate phosphine ligands. Investigation of a series of rhodium phosphine complexes showed that the position of the $^{103}$Rh resonance depends on the electronic character of the phosphorus ligand used.\textsuperscript{63}

1.3.2 High-Pressure IR Spectroscopy

IR spectroscopy is regularly applied to obtain information about the structure of the hydroformylation reaction intermediates.\textsuperscript{10, 12, 13, 24} Although the information obtained is limited to the carbonyl ligands, the position of the carbonyl frequencies and the number of carbonyl bands observed is informative about the coordination mode of the carbonyl ligands and indirectly of the phosphorus ligands (ee – ea equilibria). The rhodium-hydride frequency is often very weak and therefore observed in few cases only. The concentration region used for IR spectroscopy is similar to the concentration range used in catalysis experiments (<1 mM). Therefore this technique gives a realistic view of the intermediates present during the reaction.\textsuperscript{10, 12, 13, 24}

Similar to the NMR experiments, the IR spectra must be recorded under syn-gas pressure. Last decades many new IR cells have been developed to obtain IR spectra under pressure.\textsuperscript{24, 28} One method is the application of an autoclave connected via a pump with an IR cell.\textsuperscript{7c, 28, 64} A disadvantage of this system is mass transport limitations of the gas and temperature variation in the ‘by-pass’. This may influence strongly the type of complexes present (dimer formation). An IR cell developed to avoid this problem is the CIR (cylindrical internal reflectance) cell as used by Moser.\textsuperscript{24} The IR spectrum obtained using this IR cell is that of the real intermediates and catalyst decomposition products present during the hydroformylation reaction. A disadvantage of this cell is the lower signal to noise ratio compared to a transmission cell.

The position of the carbonyl frequencies observed gives information about the structure of the complexes present (Table 1). Especially dimer and cluster formation can be observed easily, because of the different position of the bridging and terminal carbonyl frequency in the IR spectrum. Bridging carbonyl bands are observed between 1900 – 1800 cm$^{-1}$. Terminal carbonyl bands are observed between 2100 – 1900 cm$^{-1}$; the exact
position depends on the electronic properties of the phosphorus ligands and the coordination mode of the carbonyl ligands (ee or ea).\textsuperscript{17,49} Rhodium-acyl CO frequencies are often observed at approximately 1700 cm\textsuperscript{-1}, but this absorption is often weak and therefore obscured by the strong aldehyde absorption (± 1740 cm\textsuperscript{-1}) in \textit{in situ} IR experiments.\textsuperscript{12, 13, 33} Several characteristic carbonyl frequencies for rhodium-hydride complexes containing phosphorus ligands are depicted in Table 1.

Table 1. Characteristic Positions of $v_{\text{CO}}$ of Rhodium-Hydride Complexes

<table>
<thead>
<tr>
<th>Complex</th>
<th>CO Coordination Mode</th>
<th>$v_{\text{CO}}$ (cm\textsuperscript{-1})$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRhL\textsubscript{2}(CO)\textsubscript{2} L = phosphine\textsuperscript{b}</td>
<td>ee coordination</td>
<td>2030, 1970</td>
</tr>
<tr>
<td></td>
<td>ee coordination</td>
<td>1990, 1945</td>
</tr>
<tr>
<td>HRhL\textsubscript{2}(CO)\textsubscript{2} L = phosphite\textsuperscript{c}</td>
<td>ee coordination</td>
<td>2070, 2010</td>
</tr>
<tr>
<td></td>
<td>ee coordination</td>
<td>2040, 1985</td>
</tr>
<tr>
<td>HRhL(CO)\textsubscript{3} L = phosphite\textsuperscript{d}</td>
<td>-</td>
<td>2090, 2045, 2010</td>
</tr>
</tbody>
</table>

$^a$ All carbonyl frequencies presented are averaged numbers. The $v_{\text{CO}}$ will shift depending on the electronic ligand properties. $^b$ See references 17 and 24, $^c$ See references 7a, 49, 65, 67, $^d$ See references 7c and 54.

1.4 Scope and Outline of the Thesis

Many research projects are directed to the influence of steric and electronic ligand properties on the selectivity and activity of the hydroformylation reaction. Extrapolating the results of steric and electronic ligand effects, it seems attractive to design strongly $\pi$-accepting ligands that create steric hindrance close to the rhodium centre. Phosphorus amide and phosphorus amidite ligands create more steric bulk close to the phosphorus atom compared to the electron-withdrawing phosphites because of the higher degree of substitution at nitrogen compared to oxygen. Choosing the right substituents bulky, electron-withdrawing ligands are formed. This unique combination of steric and electronic properties will result in crowded, electron-poor rhodium catalysts. There are only few examples of the application of these ligands in the rhodium-catalysed hydroformylation reaction and as a result only little is known about the effect of this combination of ligand properties on the catalytic cycle.\textsuperscript{39,41,44} The work presented in this thesis is directed towards the understanding of the hydroformylation reaction mechanism using phosphorus amide and phosphorus amidite ligands. Better understanding of the reaction mechanism, the rate-determining steps and the intermediates present during the reaction will lead to an optimisation of the catalyst performance.
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In Chapter two, a new group of phosphorus diamide ligands based on a trisubstituted biuret structure will be presented. The set of ligands synthesised contain a systematic variation of electronic and steric ligand properties. Investigation of the structure of the rhodium complexes formed under hydroformylation conditions using these ligands will show the effect of the electronic and steric properties on the coordination number and coordination mode of the phosphorus ligands. Application of these ligands in the rhodium-catalysed hydroformylation reaction leads to a correlation of the catalyst structure (and indirectly the ligand properties) and the catalyst performance (activity and selectivity).

In Chapter three, the hydroformylation reaction intermediates formed with phosphorus amide ligands will be described using model complexes. One of the phosphorus diamide ligands in HRhL₃CO has been exchanged for a substrate containing phosphine ligand. Coordination of three phosphorus ligands around the rhodium centre will stabilise the intermediates and allow characterisation using NMR spectroscopy. Stepwise addition of the hydroformylation reactants will trap the various hydroformylation intermediates. Investigation of the reactivity of the intermediates and the reversibility of the subsequent reaction steps results in understanding of the catalyst selectivity and side reactions.

In Chapter four, the mechanism of the rhodium-catalysed hydroformylation reaction of 1-alkenes using a monodentate biuret-based phosphorus diamide ligand will be studied. Investigation of the reaction kinetics gives an idea about the rate-influencing steps of the hydroformylation reaction using phosphorus diamide ligands. The intermediates present during the reaction are studied in great detail using in situ high-pressure spectroscopic techniques. The structure of these 'resting states' might give an explanation for the observed selectivity. The reversibility of the various steps proposed in the hydroformylation mechanism has been investigated to understand the catalyst performance.

In Chapter five, several phosphorus amidite ligands are presented, that contain a pyrrolyl substituent. The ligand properties and catalyst performance of these pyrrolyl-containing ligands are compared with phosphinite ligands that have similar steric ligand properties but that have different electronic properties. Using these ligands, the electronic effect on the catalyst performance can be investigated with a minimal change in steric influences.
1.5 Notes and References


6. See reference 2 in Chapters 4 and 5 and references herein.


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41 Breit, B., J. Mol. Cat., 1999, 143, 143